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Production and utilization of renewable and sustainable gaseous fuel for power generation applications: A review of literature

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ABSTRACT

Alternative fuels have numerous advantages compared to fossil fuels as they are renewable and biodegradable besides providing energy security and foreign exchange saving addressing environmental concerns, and socio-economic issues as well. Therefore renewable fuels can be predominantly used as fuel for transportation and power generation applications. In view of this exhaustive experiments on the use of producer gas for both spark ignition (SI) and compression ignition (CI) engine applications for short and long term trial runs have been reported in the literature. Today, the use of biomass derived producer gas is more reliant for addressing rural power generation and is a promising technique for controlling both NO_x and soot emission levels. Researchers have found that, the brake thermal efficiency of producer gas operated single and dual-fuel engines were far lower compared to diesel/biodiesel operated engine and suggested that, this can be improved by improving the fuel properties, adopting good operating parameters or altering engine design. In order to address this, many researchers/scientists have proposed different solutions for enhancing the performance of a producer gas operated engine.

Majority of the research work is focused on the utilization of compressed natural gas (CNG) and liquefied petroleum gas (LPG) in engines operated on both single and dual fuel mode. However, use of producer gas in engines still needs more detailed studies, as this area is less investigated. Literature review suggests that the combustion characteristics of the producer gas operated engines need extensive research for a long-term use in both gas and dual-fuel engine. In this context, this paper mainly presents a literature review based on the utilization of producer gas as fuel for transport and power generation applications. Based on the review of literatures, it can be concluded that this area requires more research with long term engine operation.

Contents

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1. Introduction

Growing population around the world needs better quality of life. In the present energy scenario, demand for energy is on a continual increase. Environmental concerns and depletion of fossil fuel reserves have led to the extensive search for alternate fuels. Using biomass as a source of energy can not only reduce the dependency on imported oil, but may also benefit the environment by reducing emissions of greenhouse gases and pollutants that affect the air quality [1–9]. Biodiesels derived from vegetable oils present a very promising alternative to diesel oil since biodiesels have numerous advantages compared to fossil fuels [1–16].

Producer gas obtained by partial combustion of biomass in a gasifier can act as a promising renewable and alternative fuel for both SI and CI engine application. Most current dual-fuel engines are made to operate interchangeably, either on gaseous fuels with liquid pilot ignition or wholly on liquid fuel injection as a diesel engine. Accordingly, a dual-fuel engine tends to retain most of the positive features of diesel operation [17]. Diesel engines cannot be operated on producer gas alone without injection of a small quantity of liquid fuel because producer gas properties will not allow the ignition to take place in a diesel engine. Therefore, a diesel engine needs to be dual fueled. Quality of producer gas affects the performance of an engine. Therefore, cooling and cleaning of gas is essential to improve the quality producer gas. The composition of producer gas depends on the biomass feed stock and gasification conditions in the gasifier. These variables have a considerable effect on gas engine performance. It is difficult to reduce (nitric oxide) NO_x and smoke simultaneously due to trade off curve between NO_x and smoke emissions. One prospective method to solve this problem is to use oxygenated renewable fuels in a dual fuel engine. It reveals that 'dual fuel concept' is a promising technique for controlling both NO_x and soot emissions even on existing diesel engine [10]. However it increases HC and CO emissions. The higher CO content in the exhaust suggests that dual-fueling should not be carried out below a certain minimum load. Researchers have reported that up to 70–90% liquid fuel saving can be obtained in a dual fueled engine [17–18].

Experimental investigations on the performance, combustion and emission characteristics of SI engine with 100% producer gas alone have been reported [12–15]. Diesel engine operated on dual fuel mode using raw vegetable oil and its methyl esters and gaseous fuel induction has been also investigated [17–23]. These gaseous fuels include producer gas, LPG, CNG, biogas, and hydrogen. Issues addressing the use of CNG and LPG with liquid fuel injection in dual fuel mode were found maximum in published literatures with acceptable performance with lower emission levels. However, use of producer gas for short and long-term use in both gas and dual-fuel internal combustion engine (ICE) resulted in lower performance. Hence, dual fuel engine with producer gas induction still needs more detailed studies, as it is less investigated. Hence, in the present work, an attempt has been made to review the literatures based on the utilization of renewable gaseous fuel (producer gas) in both spark ignition (SI) engine called as gas engine and compression ignition (CI) engine using liquid fuel as injected fuels.

2. Renewable energy in India: current status, challenges and opportunities

Demand and supply, untapped potential, air pollution and environmental concern are the key drivers for renewable energy. Many villages still do not have any electricity. Per capita electricity consumption is 733 units and world average is 2596 units as per 2005 data. However, India has already installed 150,000 MW generating capacity from renewable energy and is moving towards decentralized power generation on a large scale for rural electrification. Biomass fuels in various forms are abundantly available in most of the countries. Comparing to more advanced countries, the biomass scenario in India is completely different. The GDP of India still depends on agricultural sectors; therefore huge amount of agricultural residue is available in India. It has been estimated that India has a surplus of about 120–160 million ton of agricultural residues every year. India currently has total installed capacity of 147,000 MW of which 81,859 MW (66.30%) comes from thermal power plants based on coal, gas and oil. The percentage share of renewable is 6158 MW (5%) of the total. India has a potential of the order of 19,500 MW which includes around 3500 MW of surplus power from bagasse-based co-generation, and 16,000 MW of grid power from biomass material. India has about 140 million ha of land not used productively. Already, energy plantation of about 40 million ha was done. It can fuel about 17,000 biomass gasifiers of 10 kW each. Through which about 300 MW conventional power plant capacities can be replaced [23]. Use of renewable and alternative fuels for internal combustion (IC) engines is necessary due to uncertainties associated with the future availability of fossil fuel. Biomass-based decentralized energy generation technologies offer an attractive solution to the energy crisis. One feature of renewable and alternative sources of energy is that they are well suited for developing decentralized power plants to meet the energy needs of rural and remote areas.

Bio-derived gas and liquids appear more attractive in view of their friendly environmental nature [17]. The major challenges that face the use of biomass for engine application as fuels has been reported [23–31]. Distribution, continuous availability, transformation with respect to oil sector, optimizing the renewable energy resources, investment and capital cost are major challenges. In addition, the unstable market of biomass due to lack of fully established biomass energy conversion technology is attributed to the difficulties of the biomass collection system. The optimized collection, storage and transportation method along with suitable selection of the power plant location can significantly reduce the cost related to the biomass feedstock. However, capacity building and transaction costs play major role in the renewable energy sector. They all include logistic constraints, man power and facilities. However, it may be noted that small renewable energy projects have high transaction costs during its development.

At present, generating energy from biomass is rather expensive due to its lower conversion efficiencies, and logistic constraints. In particular, the logistics of biomass fuel supply is likely to be complex owing to the intrinsic feedstock characteristics, such as the limited period of availability and scattered geographical distribution over the territory. In this context, India has implemented many control policies towards enhanced capacities in the renewable

energy sector such as in railways, rural electrification and public transport systems. India is also trying to maximize the substitution of petroleum fuel with biofuels and has created conducive environment for transformational changes through awareness and education and many new control policies. Discounts, grants, subsidies and other related incentives can be effective in overcoming the cost barrier of adopting the use of energy-efficient and renewable energy appliances. India has planned to create employment for the rural people, develop green lands and drive the economy in the socio-economic way through many policy instruments and incentives. India's mission is to create 10 million employments within 10 years. In view of this, at present India has estimated to generate 900,000 employments by 2025 in biomass gasification sector. Of which, nearly 300,000 would be in the manufacturing and 600,000 in the areas of operation and fuel supply. This is necessary to realize the dream of India to achieve sustainable development (Source: MNRE, India).

3. Use of producer gas for an engine application

Producer gas from biomass has attracted considerable attention in recent years. The process of gasification to produce combustibles from organic feeds was used in blast furnaces over 180 years ago [14]. A gaseous product was used beginning in the early 1800s for lighting and heating in America and Europe. The first public street lighting with this gas took place in London during 1807. Also, the possibility of using this gas for transportation and power generation was realized long back and was emerged first in Europe. During World War II, shortage in petroleum supplies led to wide-spread re-introduction of gasification. First, development of portable producer started in 19th century in France and Great Britain. By 1945 the gas was being used to power trucks, buses, agriculture, power generation and industrial machines. In the year 1927, approximately about 2812 km (1740 miles) distance was covered by trucks using wood, charcoal, and semi-coke and peat coke as fuels. In Germany the first gas producer-equipped trucks came into use in 1930. During 1937 in France, a total of about 140 gas producer-equipped trucks were developed. All vehicles covered 3000–5000 km (1860–3100 miles), on par with gasoline-fueled trucks. In France, during 1938, there were 6000 gas producer trucks in operation. India and rest of the world later developed such vehicles that were powered by producer gas. With the passage of decades, petroleum gained wider use as a fuel and after World War II, the lack of a strategic impetus and the availability of cheap fossil fuels led to a general decline in the producer gas industry. Research and development in the use of gas as a fuel for internal combustion (IC) engines came to a halt in most countries [14,15].

Increased oil prices in the mid-1970s have led to a renewed interest in wood gasification technology. This was realized in those countries which are dependent on oil imports and have adequate supplies of wood or other biomass based fuels [10–18]. India is one such a country, where the technology to use biomass derived fuel is essential to develop a matter of policy. Use of energy from biofuels cannot be neglected as India has comparatively more villages and about 289 million people still do not have access to electricity in the conventional sense [18,32,33]. It is imperative that any proposed system for off-grid power generation should be economically viable and should not depend on conventional fuels [17]. However under present conditions, economic factors seem to provide the strongest argument of considering gasification technology. In many situations biomass gasification can provide an economically viable system, provided the suitable biomass feedstock is easily and abundantly available. Biomass gasifier projects for decentralized power supply in India and their financial evaluation has been investigated [18,19]. India's bio-fuel policy is looking at ways to limit rising oil imports by promoting use of biofuels as an alternative renewable source of energy. Use of biofuels such as liquid fuels (vegetable oils and bioethanol) and gaseous fuel (producer gas) in an internal combustion (IC) engine for different applications proves more relevant as it provides agricultural and rural development in terms of new jobs and income generation, energy security, environmental concerns, foreign exchange savings and socio-economic issues [34–37]. Sincere and untiring efforts shall have to be made by scientists and researchers in harnessing energy from renewable and sustainable energy sources. Even though biomass derived fuels are available abundantly in India, operating an engine with producer gas is not popular. In view of this, the Government of India has announced many facilitating policies in respect to various alternative fuel technologies and systems. Therefore, the gasifier-engine decentralized system is capable of meeting most of the energy needs of rural population of India and is essential for the country's economic growth.

Use of renewable liquid and gaseous fuels is technically more competent compared to fossil diesel and their use in a diesel engine requires minor modifications. Many researchers have concluded that bio-fuels are promising fuel substitute. Minor modifications in diesel engines can allow the use of bio-fuels efficiently [38–43]. The use of renewable and sustainable liquid and gaseous fuels derived from non-edible oils and agricultural waste for energy applications avoid the conflict between food and energy security. Although short term engine tests using neat bio-fuels showed promising results and long term engine operation led to some problems [3,10,38–44], researchers have identified several ways to utilize these bio-fuels in both diesel and petrol engines [1–31]. But the use of producer gas in both diesel and petrol engines still have problems and need to be properly addressed. Producer gas generated from biomass gasification can be used to generate electricity or heat or both heat and electricity using a combined heat and power (CHP) system called integrated gasification combined cycle (IGCC or BIGCC, Biomass-fired IGCC). A number of commercial CHP plants have been well designed and developed around the world as alternatives to the use of fossil fuel for electrical power production [45]. The producer gas generation process involves partial combustion of the solid biomass under sub-stochiometric conditions in air and subsequent reduction process resulting in the formation of producer gas, composed of H_2, CO, CH_4, CO_2 and rest N_2 with a mean calorific value of 4.7 ± 0.3 MJ/kg and resulting gas is supplied to the engine. The system comprises of different components such as gasifier, filters, flow meters, pressure and temperature indicators, cooling and cleaning system. A water treatment plant for recycling the water used for cooling the gas and biomass drier using engine exhaust and cleaning/cooling of producer gas for the plant operation has been reported [1,11,20,46–50]. Some of the important activities on gasification in Asian countries have been discussed in the literature [51]. Also, gasification progress in India has been reported [1,26,27,28,52]. Latest estimates suggest that India could have as high as 30,000 MW of power from agricultural waste alone. Currently, India's installed capacity for biomass gasification for power production is small but this is expected to change due to favorable policies set by Govt. of India.

Use of producer gas is restricted to power generation applications as its use presently in automotive sector is not viable. This may be due to the fact that development of producer gas based engines is still under research and also presence of tar removal from producer gas is to be addressed properly. This problem can be solved if some advanced gasification is employed such as plasma gasification, instead of conventional biomass gasification. Plasma gasification is a newly developed gasification process and

is carried out in an oxygen-starved environment at an extremely high temperature (more than 3000 °C). This method of gasification is a dustless and less noisy method with no environmental impact and is suitable for any type of biomass. Plasma plays a major role in this type of gasification, which is an ionized gas produced by electric discharges. Plasma can heat the biomass feedstock to a temperature more than 3000 °C or higher. Therefore, under very high temperature, a biomass is converted into a combustible gas within milliseconds [45,53].

4. Gasifier system

Researchers have studied various types of gasifier systems used for heating and engine applications. Design and development of gasifier and its components have been reported by several researchers. A brief review regarding gasifier is presented.

A gasifier is a chemical reactor in which the solid fuel (biomass/charcoal) is partially burnt in a controlled atmosphere of air in the oxidation zone. The admission of air is controlled at a certain equivalence ratio. The gasification process in a downdraft gasifier, results into a gas called as producer gas and is more suitable for engine applications compared to other gasifiers as the gas is tar-free with higher hydrogen (H_2) content (about 20%) producer gas [1]. In gasifiers, solid biomass is oxidized with a stoichiometric amount of air or oxygen. Air-based gasifiers typically generate a producer gas containing a relatively high concentration of nitrogen with a low heating value between 4 and 6 MJ/m^3. Oxygen and steam based gasifiers produce gas containing a relatively high concentration of hydrogen and CO with a heating value between 10 and 20 MJ/m^3. Therefore, the quality of producer gas can be increased by subjecting the gasification process with steam. The energy required to convert steam into hydrogen is supplied by the exothermic oxidation of carbon to carbon monoxide. This results into an auto thermal process and producing hydrogen and carbon monoxide as the major combustible products [32]. The internal diameter in most downdraft gasifiers is reduced in order to create throat. The producer gas leaving a gasifier has a temperature of about 300–400 °C for wood gas and 400–500 °C for charcoal gas. The resulting gas is mixed with soot, ash and steam vapour as well as traces of tar. This in turn could cause serious problems when used directly in an engine, if not removed before the gas enters the engine. Before admitting the gas into the engine, the producer gas must be cooled and cleaned from impurities such as soot, ash, unburnt fuel, dust and tar in order to prevent engine damage. A simple and very effective method of removing solid matter from a gas stream is to filter it through cloth or some porous material. Several types of natural and synthetic fabrics such as cotton, dacron and fiberglass are commercially available. Fabric filters have an advantage of very high collection efficiency in dust removal, which cannot be matched with cyclone or scrubbers [13,14,48,54,55]. Cooling very near to atmospheric level increases the volumetric efficiency of the gas and assists in cleaning of the gas. Cleaning of gas is essential otherwise impurities will cause problems like excessive wear, carbon deposits, pitting of the valve seats, sticky valves and rings, deteriorating of lubricating oil, slow starting and heat build-up in the engine. Producer gas for internal combustion engine applications requires impurities to be removed to acceptable levels (dust < 50 mg/m^3, tar < 50 mg/m^3 and acids < 50 mg/m^3). Cleaning equipment consists of cyclones, fabric filters, scrubbers and electrostatic precipitators. The efficiency of gasifier and quality of gas output mainly depends on the system design and biomass type and its characteristics. Degraded performance of components and low quality biomass affects the product gas generation rate and quality. Proper component monitoring and maintenance can minimize performance problems [11,43]. Proximate and ultimate analysis of various biomass types and effect of equivalence ratio (ER) on the performance of downdraft gasifier has been investigated by Zainal et al. [56] and Pratik et al., [57]. The theoretical gasification occurs between ER values of 0.19 and 0.43. Energy loss through tar and char has been reported when ER was below 0.25, whereas at higher ER some gas is burned and the temperature inside the gasifier increased. Better performance of gasifier is obtained at an ER of 0.25, this is achieved when all the tar and char is converted into producer gas. Variation of producer gas calorific value, cold gas efficiency and gas production rate with equivalence ratio has been reported. Higher calorific value of producer gas with increased ER has been reported and the trend showed reduced value after a certain critical ER. Cold gas efficiency varies in the same pattern giving higher value at maximum calorific value. Biomass consumption rate decreased with the increased moisture content of biomass while increased as there was increased air flow rate. On the other hand, gas flow rate per unit weight of fuel increased linearly with equivalence ratio. Zainal et al. [56] have observed the specific consumption of the biomass of about 2 kg/kWh, the overall efficiency of the biomass electrical power producing system was in the range of 10–11% and the cold gas efficiency of the order of about 80%.

Various types of gasifiers are used for producing a producer gas and include fixed-bed updraft, fixed-bed downdraft, fixed-bed cross draft, bubbling fluidized bed, and circulating fluidized bed types. Differentiation is based on the means of supporting the biomass in the reactor vessel, the direction of flow of both the biomass and oxidant, and the way heat is supplied to the reactor. Fixed bed gasifiers are typically simpler, less expensive, and produce lower heat content-producer gas. Fluidized bed gasifiers are more complicated, more expensive, and produce a gas with a higher heating value [45]. Design and volume content of the cooling–cleaning system is an important aspect of the gasifier-engine system design. Engine specific modifications offer significant performance improvement. The design and sequence of components depends upon requirements of fuel and engine, but they should not offer excessive resistance to the gas flow if engine starvation is to be avoided. Hence suitable filters, cooling and cleaning system must be designed and developed. The choice of filters should not be made on technical efficiency alone but requires operational reliability as well. Proper cooling of the gas will increase the density of producer gas. Therefore, greater charge (by mass) to the cylinder can be supplied. In case of the dual fueled engine system, the time required for stabilization decreases as the gas output rate increases. Particularly, gas should be supplied to the engine only after some time lapse and not immediately after starting of the gasifier. Otherwise, the moving components of engine may wear and damage rapidly. Because, immediate supply of gas may involve the risk of higher tar content gas input to the engine. More than an hour of flaring seems to be necessary prior to the engine operation. The gas outlet temperature also seems to be substantially influenced by the nature of flow through the gasifier. The presence of tar and particulates in the gas even after cooling and cleaning is a matter of concern. The levels of both are higher than usually permissible. At high gas flow rates tar diminishes and particulates increase, whereas the reverse is true with lower gas flow rate [11]. Design and development of an open core downdraft gasifier has been carried out by Rathore et al. [58]. This was installed in M/s Phosphate India Pvt. Ltd., Udaypur, India. The designed gasifier replaces 20 l of diesel fuel consumption per hour through production of 850 MJ/h of heat. The design and development of water scrubber, filters (wet filter and dry filter) by considering retention time and gas flow rates in the filter has been reported by Mandwe et al. [48] and Pathak et al. [57]. Developed filter purifies the tar content of producer gas in the

range from 24 to 53.52 mg/m^3. About 99.35% tar absorption has been reported with newly developed filter. They have observed a pressure drop in the range of 10–25 mm of water column and total amount of tar and particulate matter of about 319 mg/Nm^3 and 53 mg/Nm^3 before and after filter. Increased pressure drop across the developed filter with increased time has been reported. This shows blockage of filter with tar and particulate matter. The tests on a pilot-scale fluidized-bed gasifier and combustion system, using variety of biomass feed stock with different nitrogen contents varying from 0.14 to 1.75 wt%, have been conducted by Huynh [59]. Results show that direct and proportional relationship between nitrogen in biomass and ammonia in the producer gas, and NO_x emissions in the flue gas. The NO_x emission levels do not vary noticeably with the overall equivalence ratio in the burner but vary significantly with increased heat rate. Brown et al. [60], Hasler and Nussbaumer [54], Hasler and Nussbaumer [61] and Lina and Baron [62] have presented the evaluation of gas cleaning technology, primarily for particulate and tar removal, as it applies to biomass gasification. They have reported that gas cleaning is necessary for internal combustion engine applications and 90% tar particle removal is easier from any cooling and cleaning systems.

Paethanom et al. [63] have investigated the various tar removal techniques such as absorption technique using vegetable oil and waste-cooking oil scrubbers for heavy tar removal, adsorption technique using rice husk and rice husk char adsorbent bed for light tar removal and combination of absorption and adsorption using vegetable oil scrubber and rice husk char adsorbent bed for heavy tar removal. An externally heated continuous type pyrolyzer reactor has been used to generate tar from rice husk feedstock. Temperature of the thermal tar decomposition process was set at 800 °C and temperature of the physical gas cleaning unit was at room temperature. The tars amounts were analyzed by two different methods, wet and dry. High molecular weight tar droplets called as heavy tar analyzed by the wet method and volatile tar aerosols called light tar analyzed by the dry method. The result showed that the absorption technique was found to be effective for heavy tar removal and the adsorption technique was capable of light tar removal. By combining vegetable oil scrubber and rice husk char adsorbent bed, 95.4% of gravimetric tar could be successfully removed. The combination system resulted in the highest tar removal efficiency with the economical feasibility. A performance analysis of downdraft biomass gasifier with rubber wood, eucalyptus wood and bamboo wood and two agricultural wastes such as wheat straw and rice straw and coconut shell using a chemical equilibrium model for the pyro-oxidation zone and chemical kinetics model for the reduction zone has been examined by Roy et al. [64]. During the experiments, fuel feed rate, equivalence ratio and feed particle size are adjusted to target the critical char bed length, constant gas production rate and pressure drop with every biomass, such that the gasifier with its accessories can be used optimally. Rating of the engine coupled with the gasifier for producing power changes when gasifier fuel was changed. It could be attributed to changes in heating value and bio-energy generation rate of the producer gas with different biomass feed stock. The char flow depends on the composition of the biomass and on the rate of reduction reactions. Changes in the gas production rate and pressure drop across the gasifier alter the operating point of the blower. Gas production rate and the pressure drop across the gasifier reduction zone are predicted as 61.6 m^3/h and 746.85 Pa, respectively. Compared to various biomass feed stocks, wheat straw resulted in maximum bio-energy generation rate and the minimum specific fuel cost (Rs./MJ of energy). Heating value of producer gases with rice straw biomass is less compared to rubber wood due to higher ash content and lower heat content of rice straw.

Gas circulation increases the efficiency of the equipment and internal temperature. This high temperature helps to reduce the tar levels in the gas. High temperature within the gasifier is distinguished by changes in the flame color. Bridging, channeling, grate control and wear of internal parts are the main operational problems during gasification [55]. Due to the advantages of converting tar into useful gases and adjusting the compositions of product gases, catalyst cracking has been of interest since the mid-1980s. Several methods have been reported for removing tar content from the producer gas. The urea method was found to be good and it can be used to produce uniform secondary support layers of ZrO_2, Al_2O_3 and mixed ZrO_2–Al_2O_3. The tar conversion with these types of supports are better; mixed support was found to be the best [62]. Researchers have identified four types of catalysts namely dolomite catalysts; alkali metal and other metal catalysts; nickel catalysts and novel metal catalysts [47]. Tar conversion in excess of 99% has been achieved using dolomite, nickel-based and other catalysts at elevated temperatures of typically1075–1175 K [47,65]. Producer gas properties and their effects on the performance of the gasifier-engine system have been reported by Sridhar et al. [20]. Type of biomass used in a gasifier significantly affects the combustion. They have reported that open core downdraft gasifier provides a better solution for production of a low tar and acceptable calorific value gas for engine applications. Balat et al. [65] and Yoshikawa [66] demonstrated the effective way of decomposition of tar and soot components in the pyrolysis gas into CO and H_2, and almost dust and tar free clean reformed gas by injection of high temperature steam/air mixture into pyrolysis gas. This type of gasification system generates low-BTU gas from solid fuels. A downdraft gasifier based power generation system of 75 kW$_e$ capacity with a suitable heat exchanger has been designed and developed by Raman and Ram [33]. A heat exchanger recycles the waste heat of the hot gas, to improve the efficiency of the system. An improved ash removal system was introduced to minimize the charcoal removal rate from the reactor, to increase the gas production efficiency. They have presented a detailed analysis of the mass, energy and elemental balance. Significant improvement in calorific value of gas and 75.0–88.4% improved cold gas efficiency of the system has been reported. Pollution due to gasification, biomass collection, biomass sizing, pelletizing and ash-related problems including sintering, agglomeration, deposition, erosion and corrosion are the main obstacles to economical and viable applications of biomass gasification technologies [47]. Several works on gasification have been reported in the literatures on gasification that have been reviewed by Asadullah [67]. Barriers in each of the steps of biomass gasification from the collection of biomass feed stock to power generation has been reported. Effects of parameters in supply chain management, pretreatment and conversion of biomass to gas, and cleaning and utilization of gas for power generation has been discussed. For transportation and biomass collection, a comprehensive research has been conducted in developing an optimized logistic system. They have reported that use of efficient gasification with advanced technologies and gas cleaning methods can produce good quality producer gas with less tar content and can significantly reduce the biomass consumption. Also, logistics and biomass pretreatment problems can be overcome. A two-stage methodology has been developed to identify the best location for biofuel production facility [67,68]. The problems related to powdered biomass feeding can be overcome by densifying bulky powdered biomass into briquetting and pelletizing. During gasification for a particular temperature, steam generated from moisture acts as a gasifying agent, reacting with volatiles and char to convert them to product gas besides taking part in water–gas shift reaction which enhances the hydrogen content in the producer gas. Once the producer gas is produced, it must have a certain percentage of burnable gas (20% CO and 10% H_2) with a minimum amount of tar content (less than 100 mg/Nm^3) and

be completely free of dust and other poisonous gases. In up draft gasifier, the gas cleaning process requires considerably higher investment cost compared to downdraft gasifier, and reduces the overall efficiency of the whole process. Therefore, the application of updraft gasification is not suitable for internal combustion engines. Benefits related to gasification under pressurized condition have been reported. Increase in the gasifier pressure reduces the tar yield. However, in the fluidized bed gasifier, increasing gasifier pressure from 0.1 to 0.5 MPa, the concentration of tar, mainly naphthalene was increased and the concentration of CO decreased, while CH_4 and CO_2 increased. Better composition with the lowest tar is of prime importance for engine applications [11,19,22,67]. The higher equivalence ratio creates more oxidation environment in the gasifier, and thus attributed to lower the calorific value of producer gas. On the other hand, lower equivalence ratio results in higher calorific value producer gas, but the tar yield is considerably higher. Air and steam mixture can act as gasifying agent; it provides suitable gas composition for gas engines with higher thermal efficiency. The utilization of a catalyst, especially, a cheap and active catalyst for gas cleaning can provide the required gas quality for gas engines. Power generation using gas or dual fuel engine requires a stringent specification of gas composition or tar concentration in the producer gas. Investigation on the number of physical and catalytic tar separation methods used in different types of updraft and downdraft gasifiers have been reported. However, the most efficient gasification with optimum parameters and gas cleaning methods can produce highly combustible gas with minimum tar content. An advanced gasification method with efficient tar cleaning can significantly reduce the biomass consumption, and the logistics and biomass pretreatment problems [67].

This section summarizes useful information on the use of gasifier system necessary for satisfactory power generation. In the case of biomass gasification, tar formation and destruction are the main issues to be investigated. Tar magnitude with updraft gasifiers being very poor, downdraft the cleanest and fluidized beds are in between updraft and downdraft gasifier. The nature of the design, operating parameters and biomass feed stock is only an influencing factor on the tar production. In downdraft gasifiers the severity of final tar cracking is comparatively high due to the conditions used to achieve a significant degree of char gasification. Gas conditioning with catalyst is promising technique for tar destruction. Downdraft gasifier provides simple and economic way of producing a low tar and calorific value gas and resulted gas is found to be more suitable for engine applications compared to other design as the gas is tar-free with higher hydrogen (H_2) content. Recent development in the gasification technology using plasma gasification proves a better choice as it results into hydrogen rich syngas, zero tar and ash in the gas. Biomass feed stock with 1 in. size, higher density, acceptably moisture and calorific value, generates better quality producer gas. Cooling of producer gas equal or very near to atmospheric conditions is essential to enhance the performance of an engine. Gasifier with open top design resulted into lower fraction of high molecular weight compounds in the hot gas and lower tar and particulate level than that of many other designs.

5. Producer gas with respect to production and its properties

Researchers have studied production of producer gas and determined its various properties. A brief review of this is presented here. The major problem in biomass gasification is to deal with the tar formed during the process. Tar derived from biomass gasification will be condensed as temperature is lower than its dew point, which then block and foul process equipments like fuel lines, filters, engines and turbines. Tar content ranging about 0.5–100 g/m^3 has been reported. However, engine applications require very low tar content, of the order 0.05 g/m^3 or less [45,65]. To achieve successful design of specific gasifier, it is necessary to know the properties of biomass feed stock and thermal behavior of the fuel to be used in the gasifier. A gasifier fuel can be selected based on the energy content of the fuel, bulk density, moisture content, dust content, volatile matters and ash and slagging characteristics [45]. The producer gas composition depends on the type of biomass, design and operating parameters used in a gasifier. Better composition of gas is obtained from good quality biomass feed stock. Biomass with a density of more than 300 kg/m^3, size 20–50 mm range with moisture content of up to 20% is best suited for gasification. Briquetted sawdust was also good biomass for gasifier application. Preparation of briquetting requires some time and becomes more expensive; with these biomass materials the producer gas generated may be low in tar, char and moisture. The other woods having low density such as agricultural residue, straw waste, Honge wood produces very low quality gas and thereby fuel consumption will increase to higher extent [10]. The energy content of gas depends on the quality and its moisture present in the biomass feed stock. High moisture content reduces the performance of the gasifier because, maximum heat is utilized for water evaporation, and also results into tar entrainment problems with pressure drop across the equipment [50,51]. Many researchers have used different biomass feed stocks for generating producer gas such as Subabul wood [11,43,69], Acacia wood and crop residue [70], coir pith [21,71], cashew nut shell [72,73], Jatropha seed husk [74], sugar cane leaf [75], Ipomoea, saw mill woody waste and Subabool wood [11,43,69,57], sesame wood or rose wood [76], Causurina species wood and coconut shells [20,46,77], olive kernels [78], citrus wood [79] and Honge wood [10,19], coconut shell [80], Babul, Neem and Honge wood [81]. The moisture content of the biomass feed stock greatly affects both operation of the gasifier and the quality of the producer gas. It also reduces the throughput of the gasifier and increases the tar production in a producer gas. Development of wet packed bed scrubber-based producer gas cooling and cleaning system and performance of the unit was evaluated by operating it at various gas and water flow rates [13,14,15].

The tar content in open top ceramic lined reactor design was considerably lower due to high quality insulating material and air distribution between nozzle and reactor top. The raw gas in the range of 50–250 mg/Nm^3 for fuel having moisture content less than 15%, beyond which it is increased to about 700 mg/Nm^3. It has been observed in literature that, size of the fuel is important to achieve certain conversion rate with acceptable quality of gas. As particle size reduces, the effective exposed surface area per unit volume of the bed increases and thus influencing the rate processes. Reduction in residence time of gas and temperature at the oxidation zone of gasifier, cracking of the higher molecular weight compounds is greatly affected. These factors increase the tar fraction in the producer gas [46,50,82]. Most of the researchers have used downdraft gasifiers, as it produces low tar and char content gas. Several investigators have studied the composition and properties of producer gas. Important properties of gas involve calorific value, gas composition, gas outlet temperature, gasification efficiency. Variety of gasifiers were used by different researchers for generating a producer gas [10,11,19,21,22,43,46,50,52,70,71,73,79,83–93]. The producer gas quality depends on the combustion temperature of an oxidation zone, design of gasifier and operating parameters. The engine rings seizing in the groove depends on tar and particulate matter content and inadequate cooling of gas. Operational methodology was adopted to prevent condensation of tar and phenolic compounds during the cold conditions of the engine. Studies on different types of gasifiers and

their respective advantages and disadvantages have been reported in the literatures. They reported that the physical property of tar depends upon oxidation zone temperature [43,83]. Comparison of biomass gasification technologies, feedstock preparation requirement for different types of gasifiers, problems/drawbacks in biomass gasification and possible solutions, operation parameters, advantages and challenges of different gasifying agents, designs and operation has been reported by Abdul Salam et al. [45] and Wang et al. [47]. Particulate dust and tar removal technologies can broadly be divided into two categories namely treatments during gasification and hot gas cleaning after gasification [65,47]. Great amount of work concerning tar reduction or reforming has been reported. Performance of an open top downdraft gasifier has been investigated by Parikh et al. [11] using sababul as biomass feed stock. Composition of producer gas mainly depends on the type of biomass feed stock used and operating parameters used. The gasifier was operated under engine suction. All properties of gas depend upon the nature of flow through the gasifier. Measurable changes have been observed when gasifier operation was changed from blower mode to direct injection (DI) and indirect injection (IDI) engine mode. Minimum tar and maximum particulate matter has been reported at maximum flow rate. Jatropha seed husk feasibility for gasification is investigated by Vyas and Singh [74] using open core downdraft gasifier. They have studied properties of Jatropha seed husk and showed that, it is one of the good biomass that can be used for gasification. Performance of gasifier in terms of calorific value, fuel consumption per hour and gasification efficiency at different gas flow rates has been reported. They observed increased quality of producer gas in terms of calorific value, composition of producer gas and gasification efficiency with the increase in gas flow rate. Maximum of about 68.31% gasification efficiency at a gas flow rate of 5.5 m^3/h has been reported.

Rajeev et al. [75] have studied biomass gasification using throttles cylindrical gasifier reactor. They have used sugar cane leaves as biomass for gasifier and checked its suitability for electricity generation. They have studied the properties of biomass used and producer gas. They observed gas flow rate of 3–4 Nm^3/kWh and calorific value of producer gas was 3.5–5.0 MJ/Nm^3. Complete study on the composition of producer gas has been studied by Shashikantha et al. [69]. They reported that the producer gas has a calorific value of 6–7 MJ/Nm^3 and which is obtained by thermochemical air gasification. They found that gas had a composition of H_2=20–25%, CO=20–25%, N_2=40–45%, CO_2=8–12%, and CH_4= 1–2%. Study on multistage hybrid biomass charcoal gasification has been reported by Bhattacharya et al. [84] to produce low tar content producer gas. Use of charcoal and air was supplied in three stages of the experimentation. Design of cyclone and gas cooler for gasification application has also been reported. Different properties of producer gas have been presented. The lowest tar content of 28 mg/Nm^3 with increased heating value of gas through multistage hybrid biomass charcoal gasification has been reported. Study on open top, staggered air entry, reburn gasifier and misconceptions of producer gas have been studied by Sridhar et al. [20,88]. Producer gas has largely been left unexploited due to perceptions, such as auto-ignition tendency at higher compression ratio and large de-rating in power due to lower calorific value. Firstly, as the laminar burning velocity being high due to the presence of hydrogen might reduce the tendency for the knock. Secondly, the producer gas is consisting of many gas species with large fraction being inert gases; they might suppress the pre-flame reactions that are responsible for knocking on account of increased dilution. Also the maximum flame temperature attainable with the producer gas being lower compared to conventional fuels, therefore, one could expect better knock resistivity. These misconceptions of producer gas are essentially related to engine compression ratio limitation due to knock and de-rating. Producer gas has high octane rating compared to natural gas and biogas. Hence, producer gas favors high compression ratio. In addition, there is a general perception that producer gas being a low-energy density fuel, the extent of de-rating in power would be large when compared to high-energy density fuels like compressed natural gas and liquefied petroleum gas. Producer gas mainly consisting of considerably higher fraction of inert gases such as CO_2 (12–15%) and N_2 (48–50%) and these gases act as knock suppressors. Typically gas composition at the time of start of engine test was 19+1% H_2, 19+1% CO, 2% CH_4, 12+1% CO_2 2%+0.5% H_20 and rest is N_2. Composition of producer gas depends on the design and operating characteristics and type of biomass feed stock used. The feedstock used for gasification is Causurina species wood and coconut shells with moisture content between 12% and 15% on dry basis. Computational results concerning the laminar burning velocity of a biomass-derived producer gas and air mixture at pressures and temperatures of the unburned mixture in a reciprocating engine has been examined by Sridhar et al. [88,89]. Based on a number of calculations at varying pressures (5–50 bar) and temperatures (630–1082 K), and equivalence ratios (0.9–1.07), an expression for estimating the laminar burning velocity was obtained with the residual gas mass fraction (0–10%). They have established the relation called laminar burning velocity (S_L) by considering varying residual gas in the engine cylinder, H_2 and CO mass. This work on S_L is useful in predicting the burn rate in a spark ignition engines fueled with a producer gas. Open top design resulted into lower fraction of higher molecular weight compounds in the hot gas and lower tar and particulate level than that of many other designs. Tar content of the producer gas produced depends on the air flow distribution, temperature profile in the reactor, heat loss from the reactor and other related aspects [46,50,82,85]. Experiments have been conducted on the downdraft moving-bed gasifier with fuel–air ratio below stoichiometric [86]. Producer gas composition operating range of fuel–air ratio has been reported. Fuel–air ratio modifies the composition of the produced gas. Producer gas composition and properties are dependent on the properties of biomass and condition of gasification process. Effect of fuel–air ratio on the composition of the producer gas and best gasification conditions has been reported. Ramadas et al. [21,71] have studied downdraft gasifier, composition of biomass and compared with other biomass feed stocks. They reported that gasification of coir pith generates acceptable quality producer gas and also compared the gas properties with the various biomasses. The ratio of oxygen to biomass was used around 0.3. They have observed that the gas produced with coir pith was clean, eco-friendly and gasification with this biomass was profitable method of disposing.

Study on open core downdraft gasifier and fuel properties has been reported by Singh et al. [72,73]. They have used cashew nut shell for gasification and checked feasibility for open core downdraft gasifier. They have evaluated the performance in terms of fuel consumption rate, calorific value of producer gas and gasification efficiency at different gas flow rates. Successful gasifier operation with cashew nut shell feedstock in an open core downdraft gasifier has been reported. They conducted experiments on the gasifier using prosopis Juliflora wood as biomass in downdraft gasifier for the generation of producer gas. They have carried out proximate analysis of biomass used and reported producer gas composition. Tar and dust contents in raw producer gas obtained from this gasifier varied from 210 to 250 mg/Nm^3. The gas was further cooled and cleaned using cooling tower, organic filter and fabric filter. Then the tar content was reduced to 40–52 mg/Nm^3. The complete gas was analyzed using a gas chromatograph. They found calorific value of producer gas to be 10,420 kcal/Nm^3. Producer gas composition derived from citrus wood has been

reported by Churchill et al. [79]. They have determined the requirements for chipping and preparing citrus tree for the use in a downdraft gasifier. They have carried out fuel analysis and reported different properties of citrus wood. Suitability of citrus wood for gasification has been studied and analyzed its behavior in a downdraft gasifier. Banapurmath et al. [10,19,22] and Yaliwal et al. [23,81,93,94] have conducted experiments on the downdraft gasifier-engine system using various biomass feedstocks of different origin (Honge, Neem and Babul wood). They have reported proximate and ultimate analysis and checked their suitability for gasification. Cooling of producer gas equal or very near to atmospheric conditions is essential to enhance the performance of an engine has been reported. Biomass feed stock with 1 in. size, higher density and calorific value, generates better quality producer gas. Producer gas from downdraft gasifier using various biomasses such as coconut shell, groundnut shell and rice husk has been experimentally investigated by Sivakumar and Krishna [80] at 800 °C. Based on the results, they have showed that coconut shell is one of the good biomass feed stock for gasification. Decreased biomass consumption with increased moisture content has been reported. The calorific value of coconut shell is 23.01% higher than ground nut shell and 45.5% higher than rice husk. However, higher amount hydrogen in the producer gas for ground nut shell compared to coconut shell and rice husk has been reported. Also, producer gas generated from coconut shell has higher methane and carbon monoxide compared to ground nut shell and rice husk. Method of improving the quality of producer gas using radio frequency (RF) tar thermo-catalytic treatment reactor has been reported by Samsudin and Zainal [95]. This method resulted in higher heating value of 5.76 MJ Nm^{-3} and about 97% tar and particles conversion efficiencies with use of thermal treatment (1200 °C) and both dolomite and Y-zeolite. They have reported that low energy intensive RF tar thermo-catalytic treatment was found to be effective for upgrading the producer gas quality to meet the end user requirements and increasing its energy content. Similar results have been reported by Tang and Huang [96] using a laboratory-scale capacitively coupled radio frequency (RF) plasma pyrolysis reactor. This type of gasification requires input power of 1600–2000 W. They have conducted experiments to examine the characteristics of RF plasma reactor and the products of biomass gasification. Key parameters affecting the plasma characteristics such as plasma length, temperature, and energy transfer efficiency has been reported. Reactor pressure 3000–8000 N/m^2 produced a combustible gas that consisted of H_2, CO, CH_4, CO_2 and light hydrocarbons as well as a pyrolytic char. Gas yield up to 66 wt% of the biomass feed stock has been reported.

The effect of process parameters such as catalytic bed material, bed temperature and gasifying agent on the performance of the gasifier and quality of the producer gas has been reported by Zainal et al. [97]. They have reviewed several literatures and based on the priorities of researchers, optimum values of various desired outputs in the gasification process including improved producer gas composition, enhanced LHV, less tar and char content, high gas yield and enhanced carbon conversion and cold gas efficiency have been reported. Gómez-Barea and Leckner [98] have predicted the yield of gas composition such as CO, H_2, CO_2, N_2, H_2O, and CH_4. They have studied tar, and char conversion methods, reactor geometry and kinetic data in a fluidized bed biomass gasifier. They have used kinetics models to predict char, tar and methane conversion. They have compared the predicted data with experimental data from a 100 kW_{th} bubbling fluidized bed gasifier, operating with different gasification agents. They found nearly similar values as that of measure data. Experiments were conducted by Ouadi et al. [99] on combined heat and power (CHP) plant using paper mill rejected waste. Proximate, ultimate and gross heating value of all feedstocks used their work has also been reported. Gasification of blends of pre-conditioned paper mill rejects with mixed wood chips in an Imbert type fixed bed downdraft gasifier with a maximum feeding capacity of10 kg/h has been reported. The producer gas generated was used to produce combined heat and power (CHP) in an internal combustion engine. Gasification of waste resulted in 16.24% H_2, 23.34% CO, and 12.71% CO_2, and 5.21% CH_4 and 42.49% N_2 (v/v%) with a higher heating value of 7.3 MJ/Nm^3. Gasification with paper mill waste suffers from agglomeration problems caused by melting of plastics. Agglomeration takes place within the pyrolysis zone of the gasifier at moderate temperature levels. When the plastics become soft it becomes sticky causing bridging and binding above the gasifier throat, and this subsequently causes increased pressure drop within the gasifier unit and leads ultimately to unsuccessful gasification. Modeling of a small-scale plant based on a downdraft gasifier and a natural gas engine (spark ignition) model Cummins G855G connected to the grid has been investigated by David et al. [100] using crushed olive pits and rests of small branches and leaves as biomass feed stock. The thermodynamic model has been carried out with Thermo lib software. The mechanical model of the gas engine has been developed with Sim Drive line tool box. The connection to the grid has been carried out using Sim Power System tool box. This is used to simulate and calculate the optimum operating parameters of the plant. This biomass source could be a feasible option in gasification technology applied to distribute generation. Producer gas generated from the gasifier with crushed olive pits and small branches and leaves resulted in a calorific value of 5.1 MJ/kg and 3.7 MJ/kg respectively. Due to the higher calorific value of the producer gas and low ash content, olive pits as a feedstock for gasification has been chosen to run the gas engine. The effect of the gasification temperature in the producer gas composition shows a reduction in the percentages of H_2 and CO. Olive pits are a good feedstock for gasification to achieve the higher calorific value and low ash content producer gas. The system provides 70 kW_e and 110 kW_{th} with a biomass consumption of 105 kg/h. Electric efficiency of 14%, overall efficiency of 36% and high gasification efficiencies have been reported with such a system. Reduction in the percentages of H_2 and CO has been observed when gasification temperature falls below. To run the gas engine, around 250 m^3/h of producer gas is mixed in a modified carburetor with 350 m^3/h of atmospheric air. Reduction in 106 t per year of CO_2 has been reported with use of such system instead of natural gas use.

On the whole performance of the gasifier is greatly affected by the choice of design and operating parameters. Efficient gasification with advanced technologies, lower pressure drop across the gasifier (10–15 mm of water), efficient fabric filter and cooling–cleaning system, higher grate temperature (1200 °C), catalyst cracking of tar and use of good biomass feed stock for gasifier are adequate for proper gasification. Quality of producer gas improves when the system is operated for longer duration. An innovative method of two-stage downdraft gasification by thermal utilization concept can improve high temperature zone in the reactor and results in higher producer gas qualities with minimum tar content (50–200 mg/Nm^3). Adopting these parameters properly can produce good quality producer gas with less tar content and can significantly reduce the biomass consumption. Logistics and biomass pretreatment problems can also be overcome.

6. Performance, combustion and emission characteristics

Several literatures have studied the effect of load, speed, compression ratio, pilot fuel injection timing, pilot fuel mass, inlet

manifold condition, composition of gaseous fuel candidates vary, on the performance of the dual-fuel engines. These investigations by the researchers are conducted in both SI (100% producer gas) and CI engines (dual fuel mode) using producer gas as primary fuel and various pilot fuels derived from different vegetable oils as a injected fuel. Dual fuel engine can result in fairly better performance and extremely low smoke and NO_x emissions mainly at high power outputs compared to diesel fuel operation. Researchers have studied performance, combustion and emission parameters such as brake thermal efficiency (BTE), exhaust gas temperature (EGT), specific fuel consumption, volumetric efficiency and maximum pressure rise, heat release rate, smoke opacity, hydrocarbon (HC), carbon dioxide (CO) and nitric oxide (NO_x). These parameters depend on physico-chemical properties of fuels used, design of engine and operating conditions used during the test. Based on literatures, a brief review on the utilization of producer gas in both SI and CI engine is presented here.

6.1. Performance characteristics

6.1.1. Brake thermal efficiency

Difference in the brake thermal efficiency of both DI and IDI engines operated under dual-fuel mode has been investigated by Parikh et al. [11,101]. Better combustion efficiency was observed with IDI engines because of higher level of turbulence. Performance of a dual-fuel engine not only depends upon the pre-mixed fuel–air ratio but also depends upon the combustion chamber design of an engine. Slow speed engines are recommended for dual fuel operation because of slow burning character and lower flame velocity of producer gas.

Experimental investigations have been conducted by Banapurmath et al. [10,19,22], Ramadhas et al. [21,71], Rajeev and Anil [75], Sahoo et al. [17], Samir et al. [102], Roy et al. [103] and Dev Kumar and Reddy [104] to examine the effect of dual fuel combustion on the performance of diesel engine operated on dual fuel mode using diesel/biodiesel–producer gas combination. Lower brake thermal efficiency has been reported with producer gas fueled dual fuel engine over entire load range compared to single fuel and diesel–producer gas operation. Similar results have been reported with different raw vegetable oil–producer gas combinations. The performance of dual fuel engine depends on the quality of producer gas and on the type of biomass feed stocks for the generation of producer gas and liquid fuel used. Lower performance could be attributed to lower calorific value, higher viscosity and low volatility characteristic of vegetable oil/biodiesel in the presence of slow-burning producer gas, lower burning rate of producer gas and increased ignition delay of vegetable oils/biodiesels used in the presence of producer gas. However, increased brake thermal efficiency has been reported with use of biodiesel instead of raw vegetable oil as an injected fuel. This may be due to improved atomization, lower density, and better fuel and air mixing compared to neat vegetable oils. Further, improved performance of an engine was observed by many investigators with use of suitable carburetor as it mixes air and producer gas at stochiometric ratio [10,18,68].

The brake thermal efficiency was favored by advanced injection timing and higher injection pressure [10,105]. Advancing the injection timing and higher injection pressure increases the peak cylinder pressure because more fuel will be taking part in the combustion before top dead centre (TDC), better mixing of the fuel combination, and higher energy release rates of the mixture results in higher peak pressure and appears very closer to top dead centre (TDC). The poor performance of producer gas fueled dual fuel diesel engine at low load has been reported. This could be due to the effect of gas residuals and lower cylinder temperature. Also, reduction in combustion efficiency caused by reduced flame propagation and increased compression work resulting from the large amount of air–gas induction is responsible. Improved thermal efficiency has been reported with an advanced injection timing and increased injection pressure. Further improvement in the dual fuel engine performance has been observed with producer gas derived from high density, acceptable moisture content and low ash content biomass feed stock [10,19,81]. High density with acceptable moisture and low ash content biomass feed stock are responsible for the generation of high calorific value and higher hydrogen content producer gas. The hydrogen content in a producer gas improves the performance of dual-fuel operation because of its higher flame velocity and calorific value. Biomass such as Babul wood resulted in overall better performance compared to Honge wood. The brake thermal efficiency was lowered with use of mixed fuels–producer gas combination compared to diesel–producer gas combination [72,73]. This may be attributed to high viscosity, low volatility, and high density of vegetable oil/biodiesel, lower calorific value of mixed fuels combination. However, improvement in the thermal efficiency has been reported with increased compression ratio (CR). One of the main drawbacks of producer gas is knocking with higher compression ratio. The reason given for limiting the compression ratio was knocking tendency. It is observed that no much experimental evidence and systematic investigation had been attempted in identifying the existence of knock limitation. However, producer gas with large fraction of inert and with laminar burning velocity being high (if there is presence of H_2), smooth operation at higher CR must be possible. A systematic investigation on producer gas operation at a CR comparable to that of diesel engine has been reported in the literature [20,88–92].

Sahoo et al. [17] reviewed performance parameters such as brake thermal efficiencies, torque, fuel consumption and power output of producer gas fueled dual fuel engine. Lower performance with dual-fuel mode operation has been reported. It is due to combination of factors such as low heating value of gas, low adiabatic flame temperatures, and low mean effective pressures. Additionally, the engines are not actually designed for producer gas operation. However, focus on development of new engine designs for producer gas operation should be resolved. Suitable injector design, other parameters such as compression ratio, ignition advance, combustion chamber design, etc. are the major affecting parameters and will have to be optimized to produce higher performance with producer gas fueled dual fuel engine. The effect of hydrogen content in producer gas on the performance of a supercharged dual-fuel (producer gas–diesel fuel) engine has been studied by Roy et al. [103]. Higher brake thermal efficiency has been reported with high H_2-content producer gas i.e., increased brake thermal efficiency was observed with the use of 20% more hydrogen in a producer gas. Due to higher heating value of the H_2-content producer gas, the gas flow rate was reduced to about 6% less than low H_2-content producer gas. This is the reason why more amount of fuel was saved by using high H_2-content producer gas. Dev Kumar and Reddy [104] have reported that, the use of producer gas in a diesel engine causes 10% reduction in maximum torque as compared to diesel operation. Performance of an engine could be improved if better engine design and controls are used. However, it is possible to achieve cost savings of up to 18–25% of cost of engine in the diesel mode. Significant increase in power output from turbo charging compared to supercharging has been reported by Shaw [106]. Also a test on a diesel engine with producer gas and pilot amount of fuel injection for ignition showed decrease in power output compared to single fuel mode. Bhattacharya et al. [84] have reported that lower engine generator efficiency with dual fuel operation compared to diesel fuel operation. About 79% electrical power output has been reported for dual fuel operation compared to diesel operation. This is because of reduction in the amount of air during combustion when producer

gas was introduced. However, better combustion of producer gas is possible with minor engine modification.

Performance of producer gas and natural gas fueled SI and dual fueled CI engine at different engine load conditions have been investigated by Shashikantha and Parikh [69]. Slightly lower performance in terms of power and efficiency has been reported for producer gas fueled and diesel–producer gas operation compared natural gas operated engine. It could be due to improper hardware and connections, lack of adequate control system and part load operation of an engine with both natural gas and producer gas in dual fuel mode of operation. Experiments have been conducted by Bhattacharya et al. [84], Tinaut et al. [86], Zainal and Soid [107], Anrenfeldt et al. [108] on gas engines using producer gas alone. Investigators have observed lower brake thermal efficiency with producer gas operation. This could be attributed to low calorific value and slow burning velocity of producer gas. A parameter called Engine Fuel Quality (EFQ) has been developed by Tinaut et al. [86] to predict the engine performance working with low calorific value gaseous fuel. They have reported that the gas composition and characteristics such as heating value, stoichiometric air–fuel ratio and EFQ values affect engine power most quantitatively and predicted the engine performance based on the computer simulation. However, they have observed that indicated mean effective pressure (IMEP) obtained for producer gas was much lower than methane and isooctane. Zainal and Soid [107] studied combustion characteristics of a direct injection four stroke diesel engine using computational fluid dynamics (CFD) software fueled by producer gas. They have developed a research engine of Yanmar L60AE-DTM single cylinder engine, using IDEAS (CAD software) and exported to AVL Fire Version 8.2. By applying certain conditions, they have obtained results by computer simulation and validated against experimental results. Finally, they observed decreased engine performance and in-cylinder pressure compared to diesel operation. Combined heat and power (CHP) application with the use of producer gas have been studied by Anrenfeldt et al. [108]. They have studied CHP application under two approaches. In the first approach, the producer gas flow rate was fixed and engine was operated with varying excess air due to variation in gas composition. In the second approach the excess of air in the exhaust gas was fixed, in which the flow rate of producer gas was varying. Lower performance of the system has been reported. It was mainly due to variations in the gas composition. However, constant flow with constant gas composition resulted in the stable engine performance. Experiments on the gas engine, converted diesel engine and dual fuel engine have been conducted by Ravindranath et al. [26], Dasappa et al. [46,50,82,85], and Sridhar et al. [20,88,90]. They have investigated the overall system performance with respect to biomass and fossil fuel consumption for dual fuel operation. About 12–15% reduced thermal efficiency compared to diesel operation has been reported. For single fuel operation they found maximum efficiency of about 30% at nominal rating of the engine. Reduction in the efficiency is mainly due to minimum energy contribution from diesel and major portion of the energy is from the producer gas. Also, diesel fuel is having higher calorific value, shorter delay period and higher flame velocity compared to producer gas. However, higher thermal efficiency with diesel engine has been reported compared to converted diesel engine and dual fuel engine when these engines were operated on producer gas. Performance and impact of a decentralized biomass gasifier-based power generation system in an unelectrified village has been investigated by Ravindranath et al. [26] and Dasappa et al. [46,50,82,85]. They have investigated the effect of producer gas quality on the engine performance and response to load changes. In their research work, they have converted diesel engine into producer gas engine, which was operated at higher compression ratio of about 17. Smooth engine operation with producer gas at a compression ratio 17 has been reported. This is due to generation of smooth pressure curve and absence of knocking. Development of producer gas fueled reciprocating engines over a time frame of 6 years was studied by Sridhar et al. [20,88,90]. They have designed a suitable carburetor for producer gas operation to achieve stochiometric air–producer gas mixing. They have investigated the performance of three different engines, such as E1, E2 and E3 and are multi-cylinder naturally aspirated diesel engine, 12-cylinder in-line gas engine, and naturally aspirated six cylinder four stroke turbocharged gas engine respectively. Engine E3 gave maximum output of 60 kW at an ignition advance of 22–24° BTC when pure natural gas was used. This was mainly due to ignition timing advancement compared to engines E1 and E2 and it may be related to the combustion chamber design. They have also studied dual-fuel engine operated with diesel and producer gas induction and compared with gas engine using 100% ultra-clean producer gas. Lower thermal efficiency has been reported with dual-fuel engine compared diesel operation. Higher exhaust temperatures from the dual fuel engine may be responsible for this trend. Dasappa and Sridhar [50] have addressed about methodology and analysis towards choice of a diesel engine to meet the specific power requirement. They have evaluated both gasifier and diesel engine in terms of performance and emission characteristics. Approximately about 20% lower power output and 75% diesel savings have been reported for dual fuel operation. It could be due to lower mixer density and maximum percentage of producer gas substitution respectively as in case of dual fuel engine.

Raman and Ram [33] have studied the performance of an IC engine fueled with 100% producer gas at variable load conditions. The engine was coupled with a 75 kW_e power generator. They have compared the operation with natural gas and diesel operation. Overall power generation efficiency of 21% at about 85% load has been reported with producer gas operation. They have mainly studied the influencing factors such as volumetric efficiency, energy density of the fuel mixture; adiabatic flame temperature; compression ratio and expansion ratio. Also, they have established a relation between volumetric efficiency, expansion ratio, compression ratio and thermal efficiency. Effect of compression ratio, various biomass feedstock and HOME–bioethanol (BE) blends have been investigated by Yaliwal et al. [93] on the performance of single cylinder four stroke direct injection diesel engine operated on HOME–producer gas combination. Slightly higher thermal efficiency has been reported with higher compression ratio, high density and calorific value biomass feed stock and BE5 blend. Higher octane number of producer gas favors higher compression ratio, better quality producer gas due to burning of better quality biomass in a gasifier and proper mixing of fuel combination with air due to bioethanol blending are responsible for this trend. However, reduced performance has been reported with higher bioethanol blending. The difference in the fuel's input chemical availability and higher latent of vaporization of bioethanol might be the reason for this observed trend. Effect of producer gas flow rate (4 lpm, 6 lpm and 8 lpm) on the performance and emission characteristics of a single cylinder, four stroke air cooled engine developing power of 4.4 kW at a rated speed of 1500 rpm running on a dual fuel mode has been studied by Shrivastava et al. [109]. They have reported lower liquid fuel consumption and brake thermal efficiency compared to single fuel operation with higher flow rate of producer gas. Pisarn et al. [110] have investigated the effect of pilot fuel quantity on the performance of single cylinder, direct injection, diesel engine operated on diesel–producer gas combination. They have controlled the combustion process in a dual fuel engine by controlling the pilot fuel quantity. During test runs, load on the engine are varied between 0 and 535 kPa and

pilot fuel quantities are varied between 0.22 and 0.35 kg/h with an increment of 7 kg/h. Increased efficiency and lower CO emissions at low engine load and decreased diesel saving with exceeded pilot fuel quantity has been reported.

6.1.2. Exhaust gas temperature

Vegetable oils and biodiesels in single fuel and combinations of these oils with producer gas in dual fuel mode have been investigated by Banapurmath et al. [10,19,22], Singh et al. [72,73], Ramadhas et al. [21,71], Rajeev and Anil [75], Sahoo et al. [17], Samir et al. [102], Roy et al. [103], Parikh et al. [11,101], Dasappa and Sridhar [50] and Dev Kumar and Reddy [104]. Dual fuel operation with producer gas resulted in increased exhaust gas temperature (EGT). It depends on energy supplied to the engine and it was excess in case of dual fuel mode of operation. However, lower exhaust gas temperature at advanced injection timing for all the fuel combinations has been reported. It could be due to better combustion at advanced injection timing. They had also studied the effect of carburetor type and biomass fed stock. However, studies on the effect of carburetor showed improved performance with lower EGT. The carburetors used in their study were parallel flow, basic, Y-shaped, 90 °C, 60 °C and 30 °C gas flow carburetor. Lower EGT has been reported with parallel flow gas entry carburetor compared to Y and Basic carburetors, Y-shaped, 90 °C, 60 °C and 30 °C gas flow carburetor. Also, they have observed lower EGT with ordinary (Babul) wood compared to Honge wood over the entire load range. Lower calorific value and high moisture present in the Honge wood resulted in higher EGT due to the result of lower brake thermal efficiency. Lower EGT with carburetor and good biomass are mainly due to premixed combustion and reduced diffusion combustion phase [10,19,22]. The gasifier-engine system was analyzed for various producer gas–air flow ratios and at different load conditions by Ramadhas et al. [21,71]. They have reported that excess energy supply and increase in producer gas flow to the engine is responsible for higher EGT in a dual fuel engine and this feature leads to increased NO_x emission levels. The same author in 2008 [71] analyzed EGT for various producer gas–air flow ratios and at different load conditions. They have reported that the lower EGT for diesel operation compared to rubber seed oil, diesel–producer gas and rubber seed oil–producer gas operation.

Variations in EGT for both DI and IDI engine operated on dual fuel mode with producer gas induction has been investigated by Parikh et al. [11,101]. They have observed higher EGT for dual fuel operation compared to diesel operation. They showed that the EGT of IDI engine under dual fuel operation was very close to that of diesel operation and reported that this is because of high degree of turbulence which helps to achieve higher efficiency and more complete combustion. They found higher EGT for dual-fueled DI engine and reported that this is because of late burning of producer gas. Roy et al. [103] conducted experiments on the supercharged dual-fuel (producer gas–diesel fuel) engine operated on varying hydrogen content producer gas. They have mainly studied effect of hydrogen content of producer gas on the performance and exhaust emissions of a dual fuel engine. In their study they used two producer gases; one is with 20% H_2 and other with 13.7% H_2. Higher EGT has been reported with low H_2 content producer gas fueled dual fuel engine. But, slightly higher NO_x emission levels with high H_2-content producer gas were observed. They have reported that EGR facility could be used to reduce NO_x emissions. Sahoo et al. [17] investigated the gaseous fuel–diesel dual fueled diesel engine operation under varying load conditions. More than 100 °C EGT for dual fuel operation compared to diesel fuel mode of operation has been reported. This is due to the late and inadequate combustion time of gaseous fuels under dual fuel mode. This leads to higher exhaust gas availability for the dual fuel mode of operation. They have reported that the hydrogen content of gas has a major effect on EGT. It could be due to higher diffusion combustion taking place during the expansion stroke. Dasappa and Sridhar [50] observed that the EGT in dual fuel mode was found to be about 80 K higher than diesel mode of operation. They have reported that, this increase was due to the nature of the combustion process inside the engine cylinder. Yaliwal et al. [23,81,93] have reported higher exhaust gas temperature with dual fuel operation. However, dual fuel operation with higher compression ratio, better quality producer gas and pilot fuel of BE5 can significantly lower the exhaust gas exhaust temperature. Better combustion with improved premixed combustion and reduced diffusion combustion are responsible for the observed trend.

6.1.3. Specific energy consumption:

Specific energy consumption (SEC) was used to compare the performance of compression ignition (CI) engine operated on different fuels. In the case of dual fuel operation, SEC is the sum of energy content of both the fuels used. Increase in SEC with decreasing load both in diesel alone and dual-fuel mode has been reported. It could be attributed to considerable efficiency loss at low-load condition. SEC in dual-fuel mode is comparatively higher than the diesel mode throughout the tested load condition. Increased SEC indicates the efficiency reduction in the dual-fuel mode. This is due to reduced heating value of the producer gas–air mixture and drop in the pressure of the gas entering the air inlet and lower flame velocity Sahoo et al. [17]. Parikh et al. [11,101] have studied SEC for both direct injection (DI) and indirect injection (IDI) diesel engines operating on dual-fuel mode of operation used for agricultural applications. They reported that SEC for dual-fuel operation was higher than diesel operation over entire load range for the DI engine. However, for the IDI engine beyond a certain load with dual fuel mode gives better performance than the diesel mode of operation. Hence it results variations in SEC. Performance characteristics of a diesel engine on diesel and dual fuel mode (with producer gas) at different load conditions have been investigated by Uma et al. [70]. Higher SEC has been reported for dual fuel mode of operation compared to diesel operation throughout the tested load conditions. Increased SEC in dual fuel operation indicates reduction in efficiency. Higher SEC in dual fuel operation is due to lower flame velocity of producer gas, lower heating value of the producer gas–air mixture and drop in the gas pressure of entering the air inlet.

Higher SEC with producer gas fueled dual fuel engine has been reported by Ramadhas et al. [21,71], Singh et al. [72,73], Samir et al. [102] and Dasappa and Sridhar [50]. Ramadhas et al. [21,71] have observed that the SEC in dual fuel mode is higher than that of diesel mode of operation at all load conditions. They have reported maximum efficiency and minimum SEC at 70% load. However, lower BTE and higher SEC have been reported when dual fuel operation is above 70% load. The efficiency reduction during dual fuel is mainly attributed to incomplete combustion and increase in SEC caused by the increase in producer gas flow rate. Lower flame velocity at a relatively higher charge temperature is also responsible for this trend. Similar result has been presented by Singh et al. [72,73]. With increased percentage of RRBO during dual fuel operation, increased SEC while reduction in BTE at all load conditions has been reported. However, they have observed the decreased SEC with increased compression ratio (CR). However, the SEC in case of mixed fuel [(blend of FD+RRBO)+producer gas] mode was found to be higher than liquid fuel mode (blend of FD+RRBO). Higher SEC in liquid and gaseous fuel mixture mode may be due to higher temperature existing inside the cylinder at

the beginning of the compression stroke. Samir et al. [102] have compared the SEC obtained from dual fuel operation with diesel mode of operation. They found higher SEC for dual fuel operation compared to diesel operation at all load conditions. Higher SEC has been reported at part load conditions and irrespective of fuel used. Raman and Ram [33] have studied the performance of an IC engine fueled with 100% producer gas at variable load conditions. They have reported that gas engine with producer gas resulted in higher SEC compared to natural gas and diesel engine operation.

6.2. Emission characteristics

Emission characteristics of an engine are important as far as environmental aspects are concerned. Combustion quality can be represented on the basis of emission levels from the engine. Researchers have reported comparable results of emissions from the dual fuel engine. This is due to the variation of producer gas composition and type of liquid fuel, type of engine, design and operating parameters, engine choice (indirect/direct injection), fuel inlet temperature, high or low load and speed, operation, instrumentation accuracy, method of conducting the experiment, lack of feedstock homogeneity and ambient conditions, etc. The different emission parameters during the dual fuel mode of operation are discussed below.

6.2.1. Smoke opacity

An experimental investigation has been conducted by Parikh et al. [11,101] to examine the effect of producer gas fueled dual fuel combustion on the pollutant emissions of a DI and IDI engine. They have studied variation of carbon dioxide and oxygen contents of the exhaust from dual fuel operation with both DI and IDI engines. Increased carbon dioxide content and decreased oxygen content in both cases for all load conditions have been reported. This data collected by the investigator showed better air utilization under dual-fueling. However, under maximum diesel replacement and at rated load conditions, they were extremely unstable. Slight reduction and/or increase in gas resulted in instantaneous heavy smoke in the exhaust with engine tending to stop. Experiments have been conducted by Shashikantha and Parikh [69] on spark ignition producer gas engine (SIPGE) and compressed natural gas (CNG) engine (DCNGE). They have optimized the performance of these engines with producer gas and natural gas. Zero smoke levels and almost comparable emissions of HC have been reported from SIPGE on producer-gas or CNG operation compared to a diesel or dual-fuel engine and they have observed very low in quantitative terms, and much lower CO. Also they have observed lower nitrogen oxide emissions from SIPGE and DCNGE compared to normal diesel engines. Lower smoke opacity for diesel–producer gas operation compared to diesel operation has been reported by Banapurmath et al. [10,19,22], Ramadhas et al. [21,71] and Samir et al. [102]. This could be due to better mixing of the producer gas with air leads to clean burning of the fuel and lower liquid fuel utilization during diesel–producer gas operation. However, smoke levels for vegetable oil/biodiesel–producer gas combination under dual fuel mode operation were found to be higher than diesel–producer gas operation. This is mainly due to higher viscosity caused by the presence of free fatty acids and heavier molecular structure of Honge oil/HOME compared to diesel fuel. But biodiesel–producer gas combination under dual fuel mode of operation results in lower smoke levels compared to vegetable oil–producer gas combination. This could be due to better atomization with biodiesel injection. Smoke levels were further reduced by the use of suitable carburetor. This may be due to better mixing of air and producer gas taking place with carburetor [20,78,10]. Lower smoke opacity for biodiesel–producer gas operation has been reported with Babul wood biomass feed stock compared to Honge wood over the entire load range. Use of good quality biomass in a gasifier resulted in comparatively better quality producer gas. It could also be due to lower calorific value and higher moisture content present in the Honge wood resulted in incomplete combustion and leading to higher smoke emission compared to the Babul wood operation. Also it could be due to insufficient oxygen available for combustion and high temperature of producer gas reduces the density, which in turn reduces the mass flow rate of producer gas–air mixture required for combustion. This feature decreases the fresh air for combustion during dual fuel operation [19,23,81,93]. Similar results have been presented by Papagiannakis and Hountalas [111] and Hountalas and Papagiannakis [112]. They have observed considerably lower soot emissions compared to neat diesel operation and similar trends have been reported for all cases examined. Under normal diesel operation, soot emissions were increased with increasing engine load. On the other hand, under dual-fuel operation and for all cases examined, the soot emissions were followed the same trend with increasing engine load. It could be due to reduced liquid fuel injection and substitution of clean burning gaseous fuel, and increased charge temperature contributes to its oxidation. Yaliwal et al. [23,81,93] have reported lower smoke levels for producer gas fueled dual fuel engine. Producer gas is clean burning fuel and its use in a dual fuel engine lowers the liquid fuel consumption. Lower smoke levels were mainly due to better combustion caused by the use of higher compression ratio, better quality producer gas and better spray pattern due to better evaporation of high viscous liquid fuel. All these factors lead to complete combustion resulting lower smoke levels. Also, the use of adequate liquid fuel flow rate lowers the smoke emission levels from the dual fuel engine [109].

6.2.2. Hydrocarbon (HC) and carbon monoxide (CO) emissions

Exhaust emissions from dual fuel engine have been reported by Sahoo et al. [17]. HC and CO emissions under dual-fuel operation are considerably higher compared to the ones under normal diesel operation at low engine load. This could be due to the lower charge temperature and air–fuel ratio, resulting in slower combustion and allowing small quantities of fuel to escape the combustion process. Similar results have been reported by Banapurmath et al. [10,19,22], Ramadhas et al. [21,71], Uma et al. [70], Anrenfeldt et al. [108], Parikh et al. [11], Samir et al. [102]. It may be due to incomplete combustion of fuel used and lower flame temperature of producer gas. The HC and CO emission levels are also higher for vegetable oil/biodiesel–producer gas operation compared to diesel and producer gas combination. It could be due to lower calorific value, higher viscosity and low volatile character of vegetable oil/biodiesel in the presence of slow-burning producer gas, insufficient oxygen available for combustion, lower adiabatic flame temperature and lower mean effective pressures leads to incomplete combustion. These factors are responsible for the higher HC emissions in case of vegetable oil/biodiesel–producer gas mode of operation. The excess CO emission in the exhaust of dual fuel engine is due to the presence of already CO in producer gas itself and also due to incomplete combustion. However the HC and CO emissions for diesel–producer gas operation are comparatively lower than vegetable oil/biodiesel–producer gas fueled dual fuel engine. This is due to better combustion of diesel–producer gas combination and due to higher heat release rate for this fuel combination. These emissions were reduced slightly with the use of advanced injection timing and the use of suitable carburetors. They have reported that this is because of improved efficiency, better air–fuel mixing and higher heat release during pre-mixed burning phase rather than diffusion burning phase with producer gas–diesel fuel combination. Higher CO emission levels at part

load condition suggest the lower load limit for dual fuel operation. They have observed higher emissions under dual fuel operation with the use of low quality biomass feed stock used for generation of producer gas. Mohod et al. [16] reported that the combustion of diesel fuel with producer gas in dual-fuel operation requires more time to achieve complete combustion. It is also due to the fact that lean mixture of producer gas and pilot diesel fuel results into lower combustion. However, they reported that the CO emission levels were lowered when engine load is increased [19]. The HC and CO formation in a dual fuel engine is also examined by Heywood [113], Lavoie et al. [114], and Kouremenos et al. [115]. They reported that CO formation rate is a function of the unburned gaseous fuel availability and mixture temperature both which controls the rate of fuel decomposition and oxidation. The CO emissions under dual-fuel operation are significantly higher compared to neat diesel fuel operation. During the dual fuel operation and at low engine speed the CO emission level decreases with increased engine load. At high engine speed, the increase of engine load does not seem to affect the concentration of CO due to the less time available for combustion. In a dual fuel operation, at low engine loads, the temperature and air–fuel ratios were lower. It results in a slower combustion allowing small quantities of fuel to escape the combustion process. This further increase the HC emission levels compared to neat diesel fuel operation. However, with the increase of engine load, there is a sharp decrease of HC emissions under dual-fuel operation. It may be due to increase of burned gas temperature that helps to oxidize efficiently unburnt hydrocarbon (UBHC) emissions. Several investigators have reported that, HC and CO emissions are considerably higher under dual-fuel operation compared to neat liquid fuel operation. Advancing the pilot fuel injection timing and increased compression ratio reduces the UBHC emission levels because of better combustion due to higher temperature. The delay period increases with the increased timing advance and compression ratio and at which, increased flame propagation, better spray penetration and development was occurred. Also it results in higher combustion temperatures due to higher combustion rates of larger premixed regions. Hence it lowers the UBHC emissions. With higher injection advance, better overall combustion and the activity of the partial oxidation reactions reduce the CO emissions at advanced injection timing. For any total equivalence ratio, as the injection is retarded, the maximum charge temperature decreases. The net effect is a reduction in NO_x emission levels. However, advancing injection timing more than the limit will increase the tendency to knock.

Roy et al. [103] have studied exhaust emissions of a supercharged dual-fuel (producer gas–diesel fuel) engine. In their study they have used two producer gases; one with 20% H_2 and the other with 13.7% H_2. Within the optimum fuel–air equivalence ratio, both HC and CO emissions with the high H_2-content producer gas were 10–25% lower than that with the low H_2-content producer gas fueled dual fuel engine. Dasappa et al. [46,82,85] and Dasappa and Sridhar [50] compared the performance and emission characteristics of diesel engine operating on dual fuel mode with producer gas mode of power generation. This is because mixture of hot producer gas with air flow to the engine reduces the amount of oxygen required for combustion. This results into higher CO in the exhaust and higher exhaust temperature leading to higher losses. However, the producer gas operation alone in combustion of homogenous mixture of gaseous species results in a better combustion. Thus the overall losses are reduced amounting to better efficiencies. Sridhar et al. [20,88,89] summarized the work conducted using producer gas in reciprocating internal combustion engine. They used open top, re-burn, downdraft gasification system and 96 kW at 1500 rpm naturally aspirated diesel engine (Ashok Leyland make – ALU680 model) and 12 cylinder (V-configuration), turbo-charged – after cooled gas engine supplied originally to operate on dilute natural gas (biogas fuel) for power generation application. The gas engine used was developed from a diesel engine of model no. TBD4V12, rated at 444 kW at compression ratio (CR) of 15 and which was modified to CR of 12, to operate on gaseous fuels in a spark-ignited mode. The other modifications were carried out on the gas engine were with respect to turbo-charger (model K-28 in place of K-36) and combustion chamber (simple cylindrical bowl in place of torroidal shape). They have studied dual-fuel engine (compression ignition engine) – using high speed diesel and producer gas fuel, and gas engine (spark ignited engine) – using 100% ultra-clean producer gas. They have studied variation of CO with load and reported that higher CO emission levels in dual fuel operation compared to neat diesel operation. They found that CO levels at the rated load were about 3.1–3.5 g/MJ as against 0.6–1.2 g/MJ in diesel mode and this is due to incomplete combustion and the result of combustion inefficiency. Bilcan et al. [116] have conducted experiments on SI engine using producer gas derived from agricultural and municipal waste and wood residues. Higher HC and CO emission levels have been reported. It could be due to low energy content and the presence of certain non-combustible gases like CO_2 and N_2 in a producer gas. The use of these gases in SI engines is associated with problems like unstable operation and high levels of HC and CO emissions. Yaliwal et al. [23,81,93], Shrivastava et al. [109], and Pisarn et al. [110] have investigated the concentration of HC and CO pollutants with dual-fuel mode (producer gas) at different load conditions. Higher HC and CO emission levels have been reported during all test runs. They have claimed that this could be attributed to incomplete combustion of the fuel combinations used. However, slightly reduced emission levels have been reported with the use of lower pilot quantity and compression ratio, better quality producer gas induction and the use of lower quantity of bioethanol blending with base injected fuel. Taking these into consideration for dual-fuel operation and efficient way to reduce soot concentration is to use high percentage of producer gas with all favorable gasifier and engine conditions.

6.2.3. Nitric oxide emission

Increased producer gas flow rate results into a decrease of NO_x concentration in the dual fuel engine exhaust compared to the one under normal diesel operation. At high engine load and low input/flow rate of producer gas, there is a sharp increase of NO_x concentration in the exhaust, compared to part load conditions. The reduction of NO_x concentration is due to several factors; the less intense premixed combustion, the reduction of gas temperature due to increase of the specific heat capacity, the slower combustion and finally, the reduction of oxygen concentration due to the presence of the gaseous fuel, which replaces an equal amount of air in the cylinder charge. The variation of emission levels in the engine exhaust gas is consistent with the quality of the combustion process taking place inside the engine [17]. This is in good agreement with the already published literatures. Lower NO_x emission levels for dual fuel operation have been reported by Banapurmath et al. [10,19,22,94], Sahoo et al. [17], Uma et al. [70], and Singh et al. [72,73]. It may be due to lower flame temperature and calorific value of producer gas resulting in lower heat release during premixed combustion phase. The use of vegetable oil/biodiesel–producer gas combination further results into lower NO_x emissions compared to diesel–producer gas operation. Lower adiabatic flame temperature of producer gas, higher viscosity of injected vegetable oils/biodiesels, heavier molecular structure due to presence of free fatty acids in the fuel used and absence of organic nitrogen in producer gas are responsible for lower NO_x emission levels. However, increased NO_x levels at increased

compression ratio, injection pressure and advanced injection timing for all the fuel combination has been reported. This may be due to more time available for complete combustion and increased heat release rate. Further, decreased NO_x emission levels were observed with all fuel combinations under dual fuel mode of operation when operated with suitable carburetor. The lower NO_x emissions from the dual fuel engine are also due to the use of low calorific value and less dense biomass feedstock for generation of producer gas [19,23,81,93]. Emission characteristics of single cylinder four stroke diesel engine operating on low calorific value gas with excess hydrogen has been investigated by Masahiro et al. [51]. Slightly higher NO_x emission levels have been reported when hydrogen was mixed with low calorific value gas (producer gas). Samir et al. [102] have reported that increased NO_x emission levels with increase in load for all the fuels tested. But, it was comparatively lower than single fuel operation. It could be due to the reason of reduction in organic nitrogen from air causes lower NO_x formation. Two control approaches have been studied by Anrenfeldt et al. [108] in a dual fuel engine. In the first approach, the producer gas flow rate was fixed and engine was operated with varying excess air due to variation in gas composition. In the second approach the excess of air in the exhaust gas was fixed, in which the flow rate of producer gas was varying. They have reported that, at optimal control approach regarding gasifier operation, results in engine operation with significant variations in NO_x emissions. Ammonia in the producer gas is produced from nitrogen that is present in the biomass feed stock and is formed during the thermal process in the gasifier. It has direct effect on the emissions of gas engine. In a lean burning gas engine, the ammonia in the producer gas will oxidize and the products of N_2 and NO are formed. However, NO_x emissions were found to be below the regulated limit in dual fuel engine.

The effect of oxygen concentration and high charge temperature on nitric oxide (NO_x) emission for a dual fuel engine has been investigated by Heywood [113] and Lavoie et al. [114]. Formation of nitric oxide (NO_x) mainly depends on the high oxygen concentration and charge temperature and presence of gaseous fuel–air mixture. For the same operating conditions, concentration of NO_x under dual-fuel operation was found to be lower compared to neat diesel fuel operation. When dual fuel engine was operating at low loads, the rate of premixed controlled combustion of the gaseous fuel is lower. This leads to lower temperature inside the combustion chamber. Hence at lower and higher engine loads, the NO_x concentration was found to be lower compared to neat diesel operation. However, during dual fuel operation and at the same operating conditions, increased NO_x emission levels have been reported with higher engine load. Also reduced level of NO_x values was found to be lower at increased engine speed under dual-fuel operation compared to neat diesel operation. Yaliwal et al. [23,81,93] and Shrivastava et al. [109] have investigated the concentration of NO_x pollutant levels in a dual-fuel mode of operation (producer gas) at different load conditions. Lower NO_x emission levels have been reported during all test runs. They have claimed that, this could be attributed to lower heat release rate and incomplete combustion caused by the fuel combination used. However, slightly higher NO_x emission levels have been reported with the use of higher pilot quantity and compression ratio and with the use of lower quantity bioethanol blending with base fuel. However increased NO_x levels have been reported with increased pilot fuel [109]. Dasappa et al. [50,82] investigated variation of nitric oxide (NO) at varying compression ratio with ignition advance. The NO_x emission levels were higher at higher compression ratio and advanced ignition timings. However, they have also reported that the NO_x levels were reduced with retarding ignition timing. Similar results have been reported for all compression ratios. NO_x emission is strongly dependent on the temperature and residence time in the combustion chamber. If the flame speed of the gas mixture being high and injection timing is retarded, then the residence time in the high temperature combustion chamber is automatically reduced thereby helping in reduced NO_x generation. Sridhar et al. [20,88–92] conducted experiments on gas engine using 100% producer gas and dual fuel engine using diesel–producer gas combination. For the work, in order get air–fuel ratio at stoichiometric, they had designed suitable carburetor and studied variation of NO_x levels with load. Lower NO_x emission levels in dual-fuel engine have been reported compared to diesel engine operation. This was mainly due to lower flame temperature. Compared to dual fuel engine, a gas engine operated on 100% producer gas resulted in reduced NO_x levels. However the CO emission levels were higher in case of dual fuel operation compared gas engine and reported that it was due to reduced combustion temperature and combustion inefficiencies.

6.3. Fuel substitution

Maximum amount of liquid fuel that can be substituted by the supplementary fuel is given prime importance as in case of dual fuel engine. Many researchers have reported the lower loss of power under maximum liquid fuel substitution. The maximum substitution is decided by ignition requirements. Decrease in liquid fuel substitution leads to unsteady operation of dual fuel engine. It should be noted that liquid fuel substitution is optimized without deterioration of any performance of dual fuel engine. In such a case it leads to derating of the engine. The dual fuel engine cannot be operated below certain low load because the air–fuel mixture becomes leaner and leaner at very low load and this supplementary fuel emits out without burning. Many researchers have reported that about 40–90% liquid fuel saving. The maximum liquid fuel substitution depends on the engine operating conditions and fuel properties such as calorific value, cetane number, viscosity, density of both liquid and gaseous fuels used [11,110,10,19,22].

Liquid fuel (vegetable oil/biodiesel/diesel) substitution at different load conditions and injection timings and with use of various carburetors has been reported. Higher fuel substitution at lower loads and decreased fuel substitution with increased load has been reported. Similar results have been reported for all injection timings and carburetors used. The maximum fuel substitution is given prime importance in a dual fuel mode of operation. Fuel substitution depends on injected fuel properties and operating parameters. Lower fuel substitution has been reported for vegetable oil/biodiesel–producer gas mode of operation compared to diesel–producer gas operation. It could be attributed to lower calorific value, higher viscosity and density of vegetable oil/biodiesel used. They have observed improvement in percentage of fuel substituted with all dual fuel combinations when operated with carburetor. About 50–70% liquid fuel saving has been reported for Rubber seed oil, Honge and HOME biodiesels [10,19,22,72,73,21,71,75,17,102]. Fuel substitution during dual fuel operation has been investigated by Parikh et al. [11,101]. They have reported that the DI engine has a high diesel replacement compared to IDI engine over the tested load range. But at overload conditions, lower diesel replacement has been observed. When additional surge tank was used, then the diesel replacement was increased from 70% to 82%. It became possible to reach full load with 60% diesel replacement. The diesel replacement in DI engines was found to be better than IDI engines. It could be attributed due to the fact that excess air provision was made in a DI engine. Fuel substitution in a diesel engine operated on dual fuel mode using diesel–producer gas combination has been examined by Uma et al. [70]. Diesel replacement in the range of 67–86% has been reported. Decreased diesel replacement rate has been observed at low and high-load conditions. Samir et al. [102] obtained fuel substitution for dual fuel engine in the magnitude of 42%, 46.10%,

55.5%, 60.36% and 26.24% at 0, 25%, 50%, 75% and 98% load respectively. Decreased liquid fuel substitution at high load has been reported. Insufficient gas flow rate, variation in the gas composition and intermittent gas supply are the reasons for this trend. Slightly higher fuel substitution has been reported by Banapurmath et al. [19] and Yaliwal et al. [81] with the producer gas derived from high density and calorific value biomass. Higher density and calorific value and acceptable moisture content of biomass resulted in better quality producer gas compared to the one which is derived from low quality biomass feed stock (Honge wood). They have reported that the percentage savings of vegetable oil were found to be lower compared to that of diesel fuel in dual fuel mode operation because diesel fuel has higher calorific value and better fuel burning qualities. Decreased diesel or vegetable oil/biodiesel (pilot fuel) savings up to 72% at higher loads has been reported. It may be due to lower calorific value of producer gas and the incomplete combustion. Similar results have been reported with a dual fuel engine operated on biodiesel derived from rubber seed oil and producer gas derived from coir pith and wood chip [21,71]. Singh et al. [72,73] have investigated the effect of liquid fuel type on the fuel substitution. They have used two types of fuel namely raw rice bran oil + producer gas and diesel + raw rice bran oil + producer gas. Decreased brake thermal efficiency has been reported during dual fuel operation compared to single fuel operation and is dependent on the type of fuel combination and share of the producer gas in the liquid fuel–producer gas mixture. Liquid fuel replacement was increased with the increase in engine load and starts to decrease when engine load is further increased. The thermal efficiency depends on the replacement of liquid fuel. Up to 72–92% diesel replacements has been reported by Rajeev and Anil [75] throughout the entire load range. This is because of low pressure drops and adequate gas flow rates at higher loads and is possible due to the use of blower during generator operation. In fact, higher gas flow rates resulted in higher diesel saving. Sridhar et al. [20,88,90] have reported maximum diesel substitution of 68% at a load of 65 kW_e, at which the oxygen fraction in the exhaust was found to be about 1.5% and diesel substitution at 71 kW_e was 36% with oxygen concentration of 1.5–1.8%. Further they have observed that engine to stall with increase in gas flow rates. Pisarn et al. [110] reported that decreased diesel saving at higher pilot diesel quantity. It could be due to the rich mixture at high pilot diesel and high engine loads.

6.4. Combustion characteristics

Effect of brake power on cylinder peak pressure and maximum rate of pressure rise for single fuel and dual fuel operation using diesel/vegetable oil/biodiesel with producer gas induction has been investigated by Banapurmath et al. [10,19,22] and Yaliwal [23,81,93]. Higher peak pressure has been reported with diesel–producer gas combination compared to vegetable oil/biodiesel–producer gas combination. Similar results have been reported for maximum rate of pressure rise with the above fuel combinations under dual fuel mode of operation. Peak pressure depends on the combustion rate and how much fuel is being used in rapid combustion period. The uncontrolled combustion phase is governed by the ignition delay period and by mixture preparation during the delay period. The mixture preparation and slow burning nature of producer gas during the ignition delay period are responsible for this trend of peak pressure and maximum rate of pressure rise. They have also studied combustion duration based on the start of combustion and 90% cumulative heat release rate. Combustion duration depends on the power output of an engine and increases with increase in power output with all the fuel combinations tested with dual fuel operation. Higher combustion duration has been reported for dual fuel operation compared to single fuel and diesel–producer gas operation. The second peak during the diffusion burning phase has been reported for vegetable oil/biodiesel–producer gas combination compared to diesel–producer gas combination under dual fuel mode of operation. This could be due to burning of fuel combination in the diffusion combustion phase rather than premixed combustion phase. It could be due to higher viscosity of vegetable oils, reduction of air entrainment and slower fuel–air mixing rates along with slow burning nature of producer gas. Improper air–fuel mixing rates during the rapid combustion phase with vegetable oil/biodiesel–producer gas operation after the ignition delay is also responsible for this trend. Therefore, more burning occurs in the diffusion phase rather than in the premixed phase with vegetable oil/biodiesel–producer gas operation. Significantly higher combustion rates during the later stages with vegetable oil/biodiesel–producer gas operation lead to higher exhaust temperatures and lower thermal efficiency. However, improvement in heat release rate was observed with biodiesel–producer gas operation compared to vegetable oil–producer gas dual fuel operation. They found higher heat release rate at optimum injection pressure and injection timings and with suitable carburetor. This may be responsible for the improved brake thermal efficiency.

Improvement in the cylinder pressure and heat release rate has been reported when dual fuel engine was operated with maximum pilot quantity, higher compression ratio, use of good biomass feed stock in a gasifier and lower percentage of ethanol in the biodiesel [81,109]. The effect combustion duration, cylinder pressure and heat release rate in a dual fuel engine has been reviewed by Sahoo et al. [17]. Higher combustion duration for dual-fuel mode of operation at low load has been reported. It has been observed decreased combustion duration with increase in load. At low loads, lower combustion duration was reported compared to single fuel operation. Also, the total brake specific fuel consumption (bsfc) for dual-fuel operation is considerably higher. This indicates a poor utilization of the gaseous fuel and it was due to the lower temperature and air–fuel ratio inside the combustion chamber of the engine, resulting in a slower combustion rate as observed from the results of the heat release rate analysis. However, at high load, due to increase in the combustion temperature, gaseous fuel utilization will be improved under dual fuel operation. But its value continues to be higher compared to the one under normal diesel operation. Sridhar et al. [20,88,90] have reported that combustion phenomena for three engines namely E1, E2 and E3. E1 is a diesel engine which was tested at varying compression ratios and engines E2 and E3 were tested at the fixed compression ratio. These two engines E2 and E3 used were factory-converted spark ignition engines from the diesel engine to operate on gaseous fuels. They have studied the effect of producer gas properties on the knocking tendency at various crank angles. Pressure data was collected for different crank angles and they found, at compression ratio of 17, E1 engine worked without knocking and gave smooth operation during the entire load range and similarly E2 engine at CR12 in the turbocharger mode gave the same result as that of E1, i.e. no pressure oscillations in pressure–crank angle diagram either at part load or at full load (wide-open throttle) conditions. They have reported that at CR17, the maximum indicated mean effective pressure (IMEP) was 5.98 bar corresponding to an ignition timing of 6° CA. However at CR11.5 which was reduced to 4.85 bar with an ignition timing of 15° CA. They compared pressure–crank angle data obtained from E1 with diesel–producer gas operation at different CRs and showed lower cycle-to-cycle variations. This may be due to faster rate of combustion occurring inside the engine cylinder. The faster rate of combustion is attributed to higher flame speeds due to the presence of hydrogen in the gas and also combustion chamber

design. Based on the literature, it is understood that the peak pressure was occurred after TDC for diesel–producer gas operation in E1 engine. This may be due slow combustion with producer gas operation.

Lapuerta et al. [117,118] studied spark ignition (SI) engine operated on producer gas and analyzed the influence of the gas composition and its thermodynamic properties such as adiabatic flame temperature, heat release on the combustion characteristics and engine performance (IMEP, cylinder pressure, etc.). Deteriorated combustion has been reported with producer gas. They have calculated gas composition as a function of the gasification conditions using the chemical equilibrium model, which considers 28 chemical species. They used chemical kinetic package of CHEMKIN III and a quasi-dimensional two-zone model to study its auto-ignition behavior and to calculate the knock tendency. Effect of hydrogen content in producer gas on the performance and exhaust emissions of a supercharged dual-fuel (producer gas–diesel fuel) engine has been investigated by Roy et al. [103]. They have studied engine performance with a producer gas induction having 20% H_2 and other with 13.7% H_2. Based on cyclic variability (COV), they have reported 2% less cyclic variability and this results in stable combustion. But, severe problem has reported, if the COV in terms of IMEP exceeds 10%. They have observed higher in-cylinder pressure and rate of heat release with higher H_2-content producer gas at different equivalence ratios and various injection timings. They have showed increased cylinder pressure with advanced injection timing and at an equivalence ratio of 0.42. Maximum cylinder pressure of 11.6 MPa at an injection timing of 14° bTDC, and reached its highest level of 14.93 MPa at 17° bTDC. They found cylinder pressure of 10.1 MPa at an injection timing of 4° bTDC and equivalence ratio of 0.65 and reached its highest level of 15.2 MPa at 7° bTDC. Karim et al. [119,120] have studied ignition delay period occurring in dual fuel engines operating on a wide range of gaseous fuels and with various inert diluents added to the intake charge. They have observed differences in the delay period between dual fuel and diesel operations. This may be attributed mainly to changes in the oxygen concentration of the charge, charge effective temperature and chemical kinetic processes. They have observed cyclic variations in terms of peak cylinder pressure. Higher cyclic variations have been reported for methane fueling compared to diesel operation. But it is smaller than spark ignition operation [120]. The ignition delay was increased with increase in power output and when pilot liquid diesel fuel quantity was reduced and extent of gas substitution was increased. They have reported that with small amount of pilot diesel fuel in the unmodified engine can lead to erratic engine performance. Greater cyclic variations are associated with low load rather than high load operation.

Bilcan et al. [116] studied a gasification process and used agricultural, municipal waste and wood residues as a feed stock. The main problem with these fuels is their low energy content. This is due to the presence of certain non-combustible gases like CO_2 and N_2. Better efficiency and low emissions can be obtained when gaseous fuels are used in diesel engines on dual fuel mode. In dual-fuel engines, the presence of these gases alters the thermodynamic properties of the intake charge and significantly influence the ignition delay of the pilot diesel fuel and hence the performance of engine. The aim of this paper is to modify an existing correlation for ignition delay in a dual-fuel engine to incorporate the effects of the gaseous fuel concentration and composition on the polytrophic index. An ignition delay correlation of a biogas dual-fuel engine was modified so that it can be used with any primary fuel. The polytrophic index was assumed to be a function of the ratio of specific heats. Further, the effect of injection timing on ignition delay was included in their study. The adapted model was introduced in a simulation program and the results of ignition delay were compared with those given in the literature for a dual-fuel engine. In addition, the correlation was used to predict the ignition delay of the pilot fuel when biogas, liquefied petroleum gas (LPG), natural gas and producer gas were treated as primary fuels. The results obtained with the new correlation have been compared with experimental values from a LPG–diesel dual fuel engine. The comparison has been made between the experimental and simulation results for a biogas dual fuel engine. Error less than 10% has been reported for both fuels. Shashikantha et al. [69] studied a 15 kW_e spark ignition producer gas engine (SIPGE). They have modified the engine with combustion chamber geometry, reduction of compression ratio from 17 to 11.5, incorporation of the ignition system and mounting of an air–gas mixer. The static ignition timing provided is 35° bTDC. About 28–32% engine efficiency has been reported. Wood based producer gas of calorific value 6–7 MJ/Nm^3 is used as engine fuel. This paper reports the development of a simulation model for estimating in-cylinder process parameters of the spark ignition producer gas engine (SIPGE) and an attempt has been made for its validation. Pisarn et al. [110] investigated the effect of producer gas quantity on the cylinder pressure and the heat release rate for dual fuel mode of operation at constant speed and pilot diesel of 1500 rpm and 0.22 kg/h, respectively. They found that combustion starts later for higher gas amount comparing to the diesel operation. Slow burning nature of producer gas during the ignition delay period is the reason for this trend of result. The knocking characteristic of different compositions of producer gas has been studied by Arunachalam and Olsen [122]. Knocking tendency of a fuel is important for an engine manufacturer as it limits the compression ratio of engine operation. A CFR F-2 engine along with a gas blending system was utilized to simulate five producer gas compositions. Methane numbers of each has been measured and effect of hydrogen (H_2) and carbon dioxide (CO_2) on knock has been analyzed by experimental testing. Addition of CO_2 increases the critical compression ratio while H_2 decreases it. The effect of CO_2 on changing the critical compression ratio was found to be over twice that of H_2. About 1% increase in CO_2 increases the compression ratio by 0.32 units and a 1% increase in H_2 decreases the compression ratio by 0.14 units. Producer gas compositions such as H_2 and CO_2 act as a knock propagator and knock suppressor respectively.

Based on the studies carried out by various researchers, it is observed that, minor engine modifications in terms of advanced injection timing, increased injection pressure and compression ratio, supercharging or turbo-charging, use of effective carburetor for mixing of producer gas and air, addition of hydrogen up to 20% enhances the overall performance of both single and dual fuel engine with reduced exhaust emission levels. Use of low tar content producer gas is required for engine application. It is also seen that turbo-charging or supercharging an engine lowers engine derating.

7. Economics of biomass gasification based power generation projects

India is a land of agriculture and is made up of 600,000 villages approximately as per the census of 2011. About 70 percent of the population depends upon agriculture for their living. The complete substitution of oil imports for the transportation, power generation is the biggest and toughest challenge for India. There are about 289 million people and approximately 1800 villages still do not have access to electricity in the conventional sense and 62,000 villages (out of 600,000 villages) that are still waiting to be wired [33,19]. Though they fall under the government's rural electrification program, it is not feasible at present to connect them to the

grid as the supply continues to be erratic. In such areas the renewable power source provides the benefit for distributed power production, such that small communities and remote villages could get access to affordable electricity. One of the latest report suggested that India could have as high as 30,000 MW of power from crop waste alone. Currently, India's installed capacity through biomass gasification for power production is small but this is expected to change soon. The capital cost per MW for a biomass gasification plant is about Rs. 5.5 crores, while the operational expenses (excluding the cost of biomass) are about Rs. 0.75 per kWh. The levelized cost of power from biomass gasification will be in the range of Rs. 2.25–4 per kWh, depending on the cost of the biomass [28]. The typical capital cost for biomass power projects range from Rs. 3.00 to 4.00 crores per MW. The cost of generation depends upon the cost of biomass, the plant load factor, and the efficiency of the conversion.

It is observed that the cost of electricity generated by renewable energy technologies is comparatively higher than electricity generated by fossil fuel sources. However, in most of the Indian villages diesel generators are the only source of power, but power from biomass gasifier based plants are considerably cheaper wherever biomass is available abundantly. Even for dual fuel operation where 20% diesel is used, the generation costs are still lower, especially with high running hours and loads. The practicability of gasifier projects depends largely on logistics. Economic feasibility of a gasifier project in a specific situation involves realistic and site-specific estimate of capital, feed stock, labor and maintenance cost, value of electricity and heat produced, net liquid fuel and energy saving. The cost involves the cost of biomass, cost of gasifier system including fuel storage, fuel feeding devices, installation, overhaul and replacement costs. The conversion efficiency of gasifier is also an important factor. Overall efficiency is the product of several efficiencies. Drying efficiency depends on the equipment design and heat source. Gasifier use may be justified on the basis of a single purpose and/or in-house need. If, additional uses can be found, the gasifier may be more attractive. Some factors to be considered are sale of excess electricity and cogeneration. Power plants with gasifier based, may be worth considering if extra capacity can be sold at a profit. The Government of India has a well-framed national policy towards biomass based MW level power projects with an objective to promote biomass power generation systems and required requisite clauses are inserted in the Electricity Act, 2003. The current potential of conversion of surplus agro and forestry residues to energy was estimated to be about 16,000 MW_e and for bagasse based cogeneration in sugar mills is estimated to be about 5000 MW. The cumulative installed capacity of grid-interactive biomass power generation and bagasse cogeneration was 1212.4 MW. India had planned to install about 50 MW power and actually achieved 75.85 MW during tenth five-year plan (up to 31 Jan 2007). Also India has a target to install about 500 MW power projects through biomass gasification. Ravindranath and Balachandra [26,27], Tripathi et al. [122], Bridgwater et al. [24,123], Banerjee [25], Nouni et al. [28], Gupta et al. [29], Buragohain et al. [30], and Arbon [124] have discussed mainly about electrification of villages from hybrid energy system. Techno-economic evaluation of biomass gasification and hybrid energy systems for remote rural area electrification has been discussed. They have reported several factors such as (i) how power supplies are shared among generators in a hybrid energy system in the most economic manner and (ii) what should be the economic operation control strategy for determining power flow among different generation units. Anil Kumar [125] has discussed economic potential of producer gas fueled irrigation and highlighted unit cost of water discharged using biomass gasifier based water pumping systems with two other commonly used conventional options, i.e. diesel engine pump set and electric motor pump set. The cost of diesel per unit of power generation is USD 0.49, but the introduction of the gasifier has reduced it to USD 0.09 per unit. Use of power generation through gasification technology benefit in terms of savings in electricity bills and increase in business hours of the commercial units (67). Aqeel Ahmed Bazmi et al. [126] reported the progress and challenges for decentralized electricity generation by biomass as per the overall concept of sustainable development. Economic gains in cost reduction of imported fossil fuels, development of bio energy will result in energy security for the East Asian countries by diversifying the energy supply. Hiremath et al. [127] discussed mainly about decentralized renewable energy, scope, relevance and applications in the Indian context and reported some of the major issues faced by the Indian power sector. Economic assessment of a mid-scale wood gasification, gas cleaning and energy conversion process, with particular attention given to electricity generation costs and tar control has been addressed by Brown et al. [128]. Hamed et al. [129] and Hiroaki et al. [130] have reported the role of biomass energy in the present energy scenario and biomass energy utilization. Problems encountered in the collection and transportation of biomass used in combined heat and power (CHP) application has been discussed. Jacek [131] investigated the performance of a distributed generation plant made up of gasifier, internal combustion engine (ICE) and organic rankine cycle (ORC) machine as a bottoming unit. They have maximized electricity production from biomass in the case where there is no heat demand for cogeneration plant. Lower efficiency of the system has been reported. Based on results, they have concluded that combined ICE–ORC system is relatively attractive from the economic point of view.

Single fuel engine using producer gas alone and dual fuel engine with non-edible oil as pilot fuel and producer gas as an inducted fuel make the system completely independent of fossil fuel. This study proves that, this is an immediate and alternative solution to generate electricity economically in remote and rural areas. Small scale gasifier systems ranging between 10 and 30 kW can be used conveniently by communities to improve the quality of their lives. This will also lower the cost of diesel per unit of power generation and results into lower green house gas and leads to sustainable development.

8. Conclusions

In recent years, producer gas has become more attractive as an alternative gaseous fuel for internal combustion engines and the fact that it is made from renewable resources. Investigators/researchers have investigated the combustion in both SI and CI engine using producer gas as a fuel. In this context, an attempt has been made to review the research studies on this important area. The overall observation based on the literatures is that, fuel type, engine operating and design parameters play an important role in dictating the combustion process and the associated performance. Some important conclusions are summarized below.

- Biomass gasification offers the most attractive alternative energy system for transport, agricultural and power generation applications. Biomass-gasifier-based power generation systems can be useful in providing decentralized electricity to remote un-electrified villages.
- Producer gas derived from biomass can be used as a sole fuel for SI engine and as a supplementary fuel for CI engines in dual fuel mode.
- Gasification reactor design, operating parameters and optimization, and reducing tar formation during biomass gasification are the primary areas of research.

- Literature review indicates that diesel/biodiesel–producer gas fueled engines results into lower brake thermal efficiency and reduced NO_x emission levels with increased smoke opacity, HC and CO emissions. The engine performance is deteriorated much with higher input or flow rate of producer gas.
- The performance of such engines could be improved by fuel, engine modifications and gasifier design modifications. Optimum injection timing, increased injection pressure and compression ratio can slightly increase the performance of dual fuel engine.
- High density, acceptable moisture and low ash content biomass feed stock result in better quality producer gas. Increased temperature of oxidation zone improves the quality of producer gas. Use of catalysts in a biomass gasification process is highly effective in the removal of tar and methane, increases the hydrogen and decreases ammonia content. Tar has a calorific value of about 36,000 kJ/kg, if it is cracked completely then it is possible to get slightly higher calorific value of producer gas.
- Indian policies towards renewable energy technology are currently considering new ideas and decisions for commercialization and marketization. India has implemented many policies and minimum price per kWh to meet investment criteria. Government of India has adopted several strategies through proper decisions, policies and announcing suitable subsidies for renewable and alternative fuels. The high cost of debt is the biggest issue facing renewable in India. The high cost of debt is the most encountered problem facing in financing of renewable energy projects. To encourage and promote renewable and alternative fuels, the nation should carry out proper price setting and forcing policy, investment cost reduction policy – which provide incentives in the form of lower investment costs and encourage the public investments in renewable energy sector. Some of the obstacles can be lowered to minimum if government and NGOs initiate the green house gas reduction and energy plantation programs.

On the whole, it seems that producer gas in single/dual fuel engine is a promising technique for controlling both NO_x and soot emissions in existing engines with slight engine hardware modification. It can be observed that the single/dual-fuel mode of operation with selected alternative fuel/combinations resulted in lower performance compared with the natural gas/diesel/biodiesel–producer gas operation. Based on the present study undertaken, it is observed that, the combustion characteristics of single/dual-fuel engine fueled by producer gas still needs detailed research. Policies with good returns and incentives, investment cost reduction and public investments in renewable energy helps to enhance the usage of renewable and alternative fuels for power generation applications. Internal combustion engines fueled by producer gas with technological advancements are convenient and economically viable and can serve as a future option for power generation applications.

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